The effects of climate on the bioaccumulation of mercury in two large-bodied fish species in northern Ontario lakes

by

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Abstract

Increasing temperatures and changing precipitation patterns in subarctic Canada are expected to alter many processes in aquatic ecosystems, including mercury bioaccumulation in fish. I investigated patterns of fish mercury concentrations across the current climatic gradient in Ontario in order to assess how future climate change might impact the provisioning of safe fish. Walleye and white sucker were sampled from 70 lakes throughout northern Ontario spanning over 9.0° of latitude and representing a range of climatic conditions (annual growing degree days 604-1599). Muscle total mercury concentrations ([tHg]) were analyzed with respect to climatic variables as well as other chemical, physical, and biological variables. Second order Akaike Information Criterion (AICc) model ranking indicated that neither temperature nor precipitation were dominant drivers of mercury accumulation in walleye or white sucker. Instead, lake and watershed physical structure and $\delta^{13}C$ best predicted white sucker [tHg], while water chemistry and fish condition best predicted walleye [tHg]. Specifically, walleye [tHg] showed a curvilinear pattern when related to [SO_4] and [DOC]. The inhibitory effect of high lake [SO_4] on mercury accumulation in fish has, to the best of my knowledge, only been theorised.

Although fish mercury accumulation is not strongly driven by the current climatic conditions, a changing climate may indirectly affect mercury availability, methylmercury production, and the rate of methylmercury assimilation into fish tissue in ways that are not yet clear to us.

Keywords

Mercury, fish, walleye, white sucker, climate, sulfate, dissolved organic carbon

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Introduction

The accumulation of mercury in fish is a health concern because mercury is a neurotoxin, and the main source of mercury to humans is through the consumption of fish (Mergler et al. 2007) . In nature, mercury exists in both inorganic and organic forms. Of the organic forms, the complexed monomethylmercury (II) cation, or simply methylmercury (MeHg), is most available for uptake by organisms (Ravichandran 2004). Methylmercury has an affinity to sulfhydryl groups within proteins in biological tissues (Faust 1992, Lemes and Wang 2009) and as a result has a tendency to bioaccumulate in organisms over time and to biomagnify through food webs (Morel et al. 1998, Watras et al. 1998). Due to biomagnification, top predator fish can have high concentrations of mercury in their muscle tissues (Cabana et al. 1994). These large-bodied fish tend to be the preferred fish to eat and consequently pose a threat to human consumers, especially those whose diet is heavily composed of fish (e.g. the aboriginal peoples of northern Canada). Fish mercury concentrations are affected by numerous environmental, limnological and ecological factors. Because most organisms in freshwater and marine food webs are ectothermic, temperature plays a major role in their vital rates, and this in turn may affect mercury dynamics in these systems. Thus, climatic conditions may exert a strong influence on mercury levels found in these organisms.

Climate change will have large implications for Boreal Shield lakes (e.g. Magnuson et al. 1997, Keller 2007), and could affect the accumulation of mercury in their resident biota. Recent studies have shown that despite reduced mercury emissions in North America, some northern Ontario fish populations have not experienced a concomitant decrease in mercury concentrations; indeed some fish populations have experienced increases in mercury levels since

the 1970's (Tang et al. 2013, Gandhi et al. 2014). A changing climate was suggested as a possible cause. Understanding the current patterns of mercury accumulation across a climatic gradient may provide insight into how mercury dynamics will be altered by a changing climate.

A warmer climate might promote the production of bioavailable methylmercury. In aquatic systems, inorganic mercury is converted to methylmercury primarily by sulfate-reducing bacteria in sediments and in the water column (Compeau and Bartha 1985, Gilmour et al. 1992). This process, termed methylation, is stimulated by higher temperatures, while demethylation rates are stimulated by colder temperatures (Wright and Hamilton 1982, Ramlal et al. 1993). Lakes in warmer climates may have higher fish mercury levels because of the stimulated mercury methylation and reduced demethylation, thereby resulting in more methylmercury available for uptake into the lake food webs. Greater methylmercury concentrations in lake water have been shown to correlate with fish total mercury concentrations (Driscoll et al. 1995).

A recent meta-analysis showed that total mercury concentrations in fish and methylmercury biomagnification rates in aquatic food webs increased with latitude on a global scale (Lavoie et al. 2013). This positive trend was attributed, in part, to a latitudinal gradient in climate, particularly temperature. Fish living in warmer temperatures tend to have faster growth rates relative to fish living in cooler temperatures (Kitchell et al. 1977), and higher growth rates in fish have been shown to correlate with decreased mercury concentrations, as the mercury ingested by faster growing fish is diluted by the more rapid increase in flesh (Simoneau et al. 2005). This process is called growth biodilution. Increased temperatures at lower latitudes not only stimulate fish growth rates, but also overall lake productivity. This in turn may enhance the effects of mercury dilution across the whole aquatic ecosystem because the total methylmercury that is

available in the lake is spread out over greater plant and animal biomass (Chen et al. 2005). Furthermore, cold water temperatures inhibit the elimination of methylmercury from fish (Trudel and Rasmussen 1997). With this in mind, I predict that fish living in colder climates with slower growth rates might have greater concentrations of mercury at a particular body size.

Climate may also impact fish mercury through the effects of precipitation. Precipitation events can enhance the atmospheric deposition of inorganic mercury to a particular location (St.Louis et al. 1995). Wet deposition of both particulate mercury compounds and gaseous oxidized mercury (Hg^{2+}) from the atmosphere in the eastern United States is predicted to be impacted by future changes in precipitation that are associated with climate change (Megaritis et al. 2014). Wet deposition of mercury to lakes enhances methylmercury accumulation in wild fish populations because of greater amounts of inorganic mercury available for methylation and subsequently for uptake by lake biota (Harris et al. 2007). There is generally less precipitation in the more northern latitudes of Ontario, and as such there may be less wet deposition of mercury there. Precipitation and temperature may influence mercury availability and accumulation in opposing ways across the latitudinal gradient within Ontario. Nonetheless, I expect the influence of temperature to affect mercury accumulation to a greater extent since there is still dry deposition of elemental mercury in the absence of precipitation.

The accumulation of mercury in freshwater fish is influenced by many other factors aside from the potential effects of climate. Watershed features, chemical and physical limnology, and ecological and physiological factors are known to influence mercury concentrations in wild fish. These drivers of mercury accumulation interact with each other, and consequently make the study of mercury dynamics in natural systems complex.

The effects of water chemistry on fish mercury accumulation have been well-researched. The relationship between fish mercury concentrations and the concentration of dissolved organic carbon ([DOC]) in the water, for example, has been evaluated in multiple studies, but with differing results. A positive trend between the accumulation of mercury in fish and DOC concentrations has been observed in some studies (McMurtry et al. 1989, Wren et al. 1991, Watras et al. 1998, Wiener et al. 2006). This positive trend has been attributed to the ability of both elemental mercury and methyl mercury to complex with DOC. This complexation facilitates the transport of mercury compounds to lakes from surrounding watersheds, and/or the promotion of methylmercury production by microbial communities that use the DOC as an organic substrate. In contrast, studies examining ecosystems with higher DOC concentrations found a negative trend between fish mercury accumulation and DOC concentrations (Grieb et al. 1990, Snodgrass et al. 2000). In these cases it is believed that DOC inhibits methylmercury production by forming strong complexes with inorganic mercury, making it unavailable to sulfate-reducing bacteria. Further to this, some studies have shown that the concentration and quality of DOC can stimulate mercury accumulation until a certain DOC threshold is reached, after which mercury accumulation is inhibited. Driscoll et al. (1995) found that yellow perch caught in Adirondack lakes generally exhibited a positive trend between total mercury concentration and DOC concentrations, except in lakes with very high DOC concentrations (> 8 mg C L^{-1}). Similarly, French et al. (2014) found that mercury concentrations in aquatic invertebrates of Canadian Arctic lakes increased with DOC concentrations up to about 8.5 mg C L^{-1}, but declined with further increases. The bioavailability of mercury might be reduced in high DOC lakes because above the threshold DOC concentration of about 8 mg C L^{-1}, the mercury

binds strongly with humic acids in the DOC rather than the lower molecular weight fulvic acids (Golding et al. 2002, French et al. 2014).

Lake water pH can affect mercury levels in fish indirectly by influencing methylmercury availability in the water and also directly through the uptake of mercury in the fish itself. Studies have shown that acidic lakes tend to have elevated total and/or methylmercury concentrations in the water column (Meili et al. 1991, Wiener et al. 2006), invertebrates (Rennie et al. 2005), and in fish (Wren and MacCrimmon 1983, Cope et al. 1990, Watras et al. 1998, Chen et al. 2005, Wiener et al. 2006). Low pH may enhance the uptake and subsequent methylation of inorganic mercury by bacteria (Kelly et al. 2003). The solubility and mobility of methylmercury may also be enhanced in acidic conditions, such that more total mercury and methylmercury are transported into lakes when surface water entering the lake is acidic (Lee and Hultberg 1990, Meili et al. 1991). The added sulfate associated with acidic water may stimulate methylmercury production by sulfate-reducing bacteria (Gilmour et al. 1992, Branfireun et al. 1999). Finally, acidic conditions may enhance the direct uptake of MeHg in fish by increasing gill permeability (Rodgers and Beamish 1983).

The size and land cover of the watershed surrounding a lake can influence the loading of mercury to the lake and as a result can influence the mercury concentrations in the fish. Wetlands within a lake's drainage basin can be significant sources of inorganic and methylmercury. As stated above, the transport of elemental mercury and methylmercury in wetlands downstream to lakes is facilitated by complexes formed between mercury and DOC (Mierle and Ingram 1991, St. Louis et al. 1994). Thus, lakes situated in wetland-dominated drainage basins tend to have high mercury concentrations in the water and fish (Greenfield et al.

2001, Rasmussen et al. 2007, Wyn et al. 2010). Additionally, lakes that have a large drainage basin relative to lake surface area receive relatively greater inputs of mercury (Suns and Hitchin 1990).

The Canadian subarctic, including part of northern Ontario, is predicted to experience some of the most pronounced effects of global climate change in the coming decades (Bernstein et al. 2007). Because mercury dynamics in aquatic systems can be influenced by climatic factors, namely temperature and precipitation, it is likely that fish mercury concentrations vary across the current climatic gradient in northern Ontario, and will shift in future as climate change advances. Even within the relatively narrow latitudinal range of this region (roughly nine degrees of latitude), differences in annual temperature, growing season length, and precipitation are substantial. Examining fish mercury patterns across this gradient will help us to understand how the accumulation of mercury in wild fish will be affected by further climate change in northern Canada.

In this study I employed a space-for-time substitution approach to examine the possible effects of climate change on fish mercury in northern Ontario. The space-for-time approach is commonly used in plant succession research, but has also been effectively used to study the influence of climate change on aquatic systems (e.g. Weyhenmeyer and Karlsson 2009, Larsen et al. 2011). Specifically, my objectives were to:

1. Evaluate how the total mercury concentrations of northern Ontario fish are related to certain climatic variables, such as air temperature, precipitation and growing season length;

2. Investigate the relationships between total mercury in these fish and various other lake and catchment-scale variables already known to influence mercury availability and uptake, and investigate these relationships in conjunction with climatic drivers identified in Objective 1.

My approach was to evaluate the effects of climate relative to the numerous other factors that can simultaneously influence the accumulation of mercury in fish. My focus was on two trophically-distinct fish species that commonly co-habit boreal lakes – the piscivore walleye (*Sander vitreus*), and the benthivore white sucker (*Catostomus commersonii*). Both species were sampled from each of 70 lakes situated along a climatic gradient in northern Ontario. Restricting my study to lakes with co-habiting populations of these species (lake as block effect) allowed me to make stronger inferences about the possible differential effects of climate and other factors on species occupying very distinct food web positions.

Overall, I predicted that mercury concentrations in both species would increase from south to north, and that fish mercury concentrations would be negatively related to indices of environmental temperature, consistent with a recent meta-analysis (Lavoie et al. 2013). My expectation was that temperature would be a primary driver but its effect on biodilution would be stronger than its effect on the production and availability of methylmercury, and hence, the net effect of declining temperature with increasing latitude would be more rapid bioaccumulation.

Methods

Study lakes

Walleye and white sucker were sampled from 70 northern Ontario lakes distributed over a climatic gradient spanning nine degrees of latitude (45°24’ N to 54°20’ N). Study lakes ranged in area from 1.2 km^2 to 2082.6 km^2 and in maximum depth from 1.8 m to 186 m. Based on existing limnological data, roughly three quarters of the lakes were considered to be oligotrophic (epilimnetic total P < 20 $\mu g\ L^{-1}$), while the remaining lakes were considered mesotrophic. None of the lakes have point source inputs of Hg, although they have varying levels of shoreline development. Several of the lakes have regulated water levels and may thus be considered reservoirs. However, in most cases the land flooded for these reservoirs was minimal, and the flooding occurred > 50 years ago.

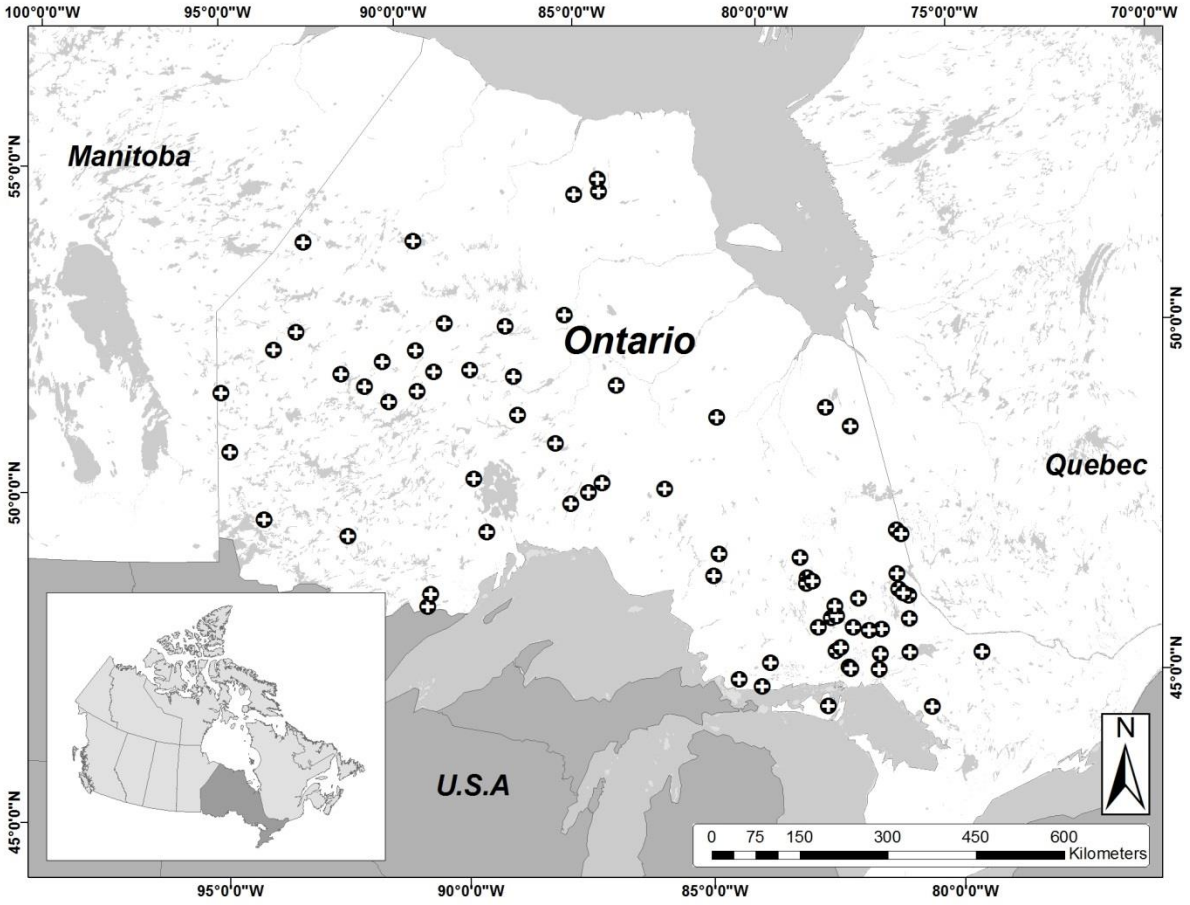

Figure 1. Locations of 70 study lakes throughout the Near and Far North of Ontario that were sampled for both walleye and white sucker.

Field collections

Walleye (*Sander vitreus*) and white sucker (*Catostomus commersonii*) were sampled from the 70 study lakes from 2008 to 2013, inclusive. Fish were primarily sampled using overnight sets of multimesh, monofilament, benthic gill net gangs of the North American 1 configuration used by the Ontario Ministry of Natural Resources and Forestry's (OMNRF) Broad-scale Monitoring (BsM) protocol (Sandstrom et al. 2010). In a few lakes, walleye and white sucker were sampled by trap net, and in some lakes walleye were also sampled by angling. In all lakes, a wide size range of each species was haphazardly selected for subsequent processing. A minimum of 10 fish of each species were processed from each lake. For each fish, fork length, total length, and round (whole body) weight were measured and recorded, a dorsal, skinless muscle sample (~ 30 – 50 g) was collected, and ageing structures were removed. Ageing structures were sagittal otoliths for walleye and pectoral fin rays for white sucker. In addition to fish, up to ten large-bodied clams (Mollusca, Unionidae) were sampled from 28 of the lakes to determine baseline isotopic signatures. Individual clams were measured for length and weight, and foot muscle was removed. Fish muscle samples were placed in small plastic bags and clam foot muscle samples were placed in glass vials, and both were stored at -20 ˚C prior to further processing.

Water samples were collected from 64 of the 70 study lakes between 2005 and 2014. Forty-four of these lakes were sampled by researchers from the Vale Living with Lakes Centre, 14 lakes were sampled by researchers at the Dorset Environmental Science Centre (DESC), and six very remote lakes were sampled by outpost owners and bush plane pilots. A surface grab (~ 0.5 m below surface) of water was collected from above the deepest area of the lake during the open-water season. Water samples were kept refrigerated until analysis. Water clarity was determined

at the same sampling location, whenever possible, by measuring the depth below the surface at which a Secchi disk is no longer visible.

Laboratory analyses: Biota and water chemistry

Fish and clam muscle tissues were dried for seven days on a Labconco Freezone 12 freeze-drier (< 0.20 mBar, < - 45 °C). The freeze-dried tissues were then ground into a fine powder using a ball mill (Retsch MM 400) and stored in glass scintillation vials. Subsamples of the powdered fish muscle were analyzed for total mercury concentration [tHg] by Atomic Absorption Spectroscopy (AAS) on a Milestone direct mercury analyser (DMA-80) at the Biotron Analytical Services Laboratory (Western University, London, ON). All mercury concentrations were expressed on a dry mass basis ($\mu g\ g^{-1}$ or ppm). Subsamples of the powdered fish and clam muscle were analyzed for carbon and nitrogen stable isotope composition at the Stable Isotopes in Nature Laboratory (SINLAB, University of New Brunswick, Fredericton, NB). Isotope analysis was conducted using two similar continuous-flow isotope-ratio mass spectrometers (CF-IRMS) depending on the time of analysis: either a Thermo-Finnigan Delta Plus or a Delta XP CF-IRMS.

Because mercury bioaccumulation depends in part on the trophic ecology of organisms, stable carbon and nitrogen isotope ratios were determined to infer the food web positions of the target species. Stable isotope ratios represent the ratio of the heavy to light isotopes ($^{13}C/^{12}C$ or $^{15}N/^{14}N$) within a sample, relative to an international standard reference material and are expressed as parts per mil (‰) (Peterson and Fry 1987, Fry 2006). Nitrogen stable isotope ratios ($\delta^{15}N$) have been shown to increase by an average of approximately 3.4 ‰ from prey to predator,

and so $\delta^{15}N$ can be used to infer trophic position (Cabana and Rasmussen 1994). Carbon stable isotope ratios ($\delta^{13}C$) vary according to particular modes or locations of primary production that support a food web. In aquatic food webs, $\delta^{13}C$ is much lower in primary production from the pelagic zone than from the benthic zone due to differences in CO_2 availability (Hecky and Hesslein 1995). But, $\delta^{13}C$ is not greatly affected by subsequent trophic transfers and can therefore be used as an index of the relative importance of pelagic and benthic production supporting consumers at all trophic levels (France 1995, Hecky and Hesslein 1995).

The age of each fish was determined by counting annular growth rings on calcified tissues at the Northwest Fisheries Ageing Lab (OMNRF, Dryden, ON). Walleye otoliths were processed by the crack-and-burn technique; otoliths were split across the transverse plane and the broken surface was lightly burned to make the annuli more visible. Annuli were counted under a dissecting scope using reflected light. White sucker pectoral fin rays were set in epoxy, thin transverse sections were cut near the base with a jeweller's saw, and the sections were mounted on glass microscope slides. Annuli in the sections were counted under a compound microscope using transmitted light.

Unfiltered water samples from the study lakes were refrigerated and analyzed within 120 h of collection at the Ontario Ministry of Environment and Climate Change's (OMOECC) Dorset Environmental Research Centre (Dorset, ON) for a suite of water quality parameters including pH, alkalinity, conductivity, nutrients, [TOC], [SO_4], and major ions (OMOECC 2015). In preparation of measuring [TOC], the particulate matter in the water samples was allowed to settle out of solution. Hereafter, I refer to this [TOC] measurement as [DOC], even though the water was not passed through a 0.7 µm or smaller filter.

Data acquisition: Lake physical limnology, drainage basin characteristics and climate

Lake physical data (e.g., surface area, mean and maximum depth) were retrieved from the Aquatic Habitat Inventory (AHI) database. Secchi depth data were also obtained from the AHI database for those lakes where Secchi measurements were not taken during field sampling. The AHI database was produced from OMNRF surveys measuring physical, chemical and biological conditions of Ontario lakes between 1957 and 1986 (Dodge et al. 1985). Drainage basin characteristics, such as area, slope and land cover, were generated from the Ontario Flow Assessment Tool, Version 3 (OFAT III, 2015), a web-based mapping application created by the OMNRF. The geographic coordinates of the outflow of each study lake were entered into this application, and the corresponding watersheds were delineated using Ontario Integrated Hydrology data (OFAT III, 2015). Lake and wetland area data used in OFAT III were sourced from the Ontario Hydro Network and Land Information Ontario, respectively (OFAT III, 2015).

Climate data were also obtained from a web-based application. Natural Resources Canada and the Canadian Forest Service developed spatial and temporal North American climate models that use historic climate data generated from Environment Canada and NOAA meteorological stations (McKenney et al. 2011). The models were created using smoothing splines on the climate data, thus allowing climate estimates to be generated at specific locations for which measured climate data would otherwise be unavailable (McKenney et al. 2006, 2011). Thirty year long-term averages (1981 to 2010) of mean monthly and annual air temperatures, growing degree days (GDD; cumulative degree days above 5°C), length of growing season (Julian date after August 1st when minimum temperature reaches $\leq$ -2°C minus the Julian date when mean daily temperature is $\geq$ 5°C for 5 days in a row), and annual and seasonal precipitation were generated from this online tool based on the geographic coordinates of each of the study lakes.

Climate estimates were only available up to the year 2010, however many of the fish used in this study were collected after 2010. For this reason, I was unable to obtain climate estimates for the entire range of years that the fish were alive, and instead used the 1981-2010 climate averages that were available from the online modelling application.

Data handling and variable calculations

Both nitrogen and carbon isotope signatures at the base of food webs vary among lakes, so it is generally recommended to adjust isotope values of other biota in the system according to these baseline values prior to analysis of differences among lakes (e.g. Cabana and Rasmussen 1996). The $\delta^{13}C$ and $\delta^{15}N$ of relatively long-lived primary consumers, such as clams or snails, are the preferred values to use for baseline adjustment (Cabana and Rasmussen 1996). I was able to obtain clam isotope data for only 28 of my 70 study lakes. In subsequent analyses with isotope data I ran the analyses twice, once on the reduced data set of 28 lakes, using baseline-adjusted values, and once using the complete data set of 64 lakes (lakes for which all types of data were available) using unadjusted values in order to examine how this may affect interpretation of results (see below). Baseline adjustment was performed for each lake by subtracting mean clam isotope values from individual fish isotope values for both $\delta^{13}C$ and $\delta^{15}N$.

I calculated the lifetime growth rate for each fish as total length divided by fish age (LGR, mm yr^{-1}). Body condition may also contribute to biodilution of contaminants, similar to the effect of growth rate. Morphometric condition indices are commonly used to represent the energetic status, and health of fish (Kaufman et al. 2007). For each population, I estimated condition as the mean predicted body mass at 440 mm for white sucker and 477 mm for walleye, the standard lengths used for body size covariation adjustment (see below).

All statistical analyses were conducted with R statistical software 3.2.0 (R Core Team 2013). I analysed the walleye and white sucker data separately, and treated each population (species x lake) as a replicate. To account for covariation of total mercury concentration, $\delta^{13}C$, $\delta^{15}N$, lifetime growth rate, and fish condition with fish size all population means were adjusted to a standard total body length using an ANCOVA approach. This standard length of comparison was calculated as the predicted total length at 1 kg from a $\log_e$ mass versus $\log_e$ total length regression model for the pooled data of all 70 lakes. The standard total lengths at 1 kg were 440 mm and 477 mm for white sucker and walleye, respectively. When standardizing mean population estimates of the aforementioned variables to these specified lengths, the variables were $\log_e$ transformed where appropriate to linearize the relationships with total length. Bivariate scatter plots were visually examined, and obvious outliers were removed.

Three values were calculated from the drainage basin estimates produced by OFAT III: the ratio of drainage basin area to lake area (D_a:L_a), the ratio of wetland area to lake area (W_a:L_a), and percent wetland area in the drainage basin. These variables were considered to be positively related to mercury inputs from the surrounding catchment. Anoxia factors (AF) were calculated as a means to quantify the extent of anoxia in the study lakes, and were included in this study because rates of mercury methylation are highest in the anoxic zones of lakes (Eckley and Hintelmann 2006). Anoxia is a function of mean lake depth, lake surface area and the productivity of the lake (Nürnberg 1996, 2004), and. Using total phosphorus and nitrogen as indicators of lake productivity, anoxia factors based on TP (AF_{TP}) and total Kjeldahl nitrogen (AF_{TN}) were calculated by the following two equations:

$$\text{Equation 2.1. } AF_{TP} = -36.2 + 50.1 * \log(TP) + 0.762 * \frac{mean\ depth}{surface\ area^{0.5}}$$

(Nürnberg 1996)

$$\text{Equation 2.2. } \mathrm{AF_{TN}} = -173 + 73 * \log(total\ Kjel\ N) + 0.925 * \frac{mean\ depth}{surface\ area^{0.5}}$$

(Nürnberg 2004)

I expected that methylmercury production, and consequently fish mercury concentration, would be positively related to all of these variables.

Many water chemistry variables are highly correlated. To account for potential multicollinearity, the water chemistry data were entered into a principal components analysis (PCA). PCA reduces the complexity of multivariate data by creating new axes, or principal components (PCs) that are uncorrelated with each other. The first component explains the most variance in the dataset, and subsequent components explain progressively less variance. The scores of the resulting PCs were extracted and used in subsequent analyses to represent water chemistry, along with selected individual water chemistry variables.

Model building and ranking

I first examined bivariate scatter plots to determine the relative strength and nature of the effects of the various predictor variables (climate, drainage basin, fish biology, lake structure characteristics, chemistry PCs, individual chemical variables) on size-adjusted population means of muscle [tHg]. Where the relationship between muscle [tHg] and a predictor variable appeared non-linear, I used $\log_e$-transformed variables or added a squared term (i.e., created a quadratic model) to linearize the relationship. Next, I regressed muscle [tHg] of each species against

combinations of the individual predictor variables using a stepwise variable selection procedure from the leaps package in R (Lumley 2009). Predictor variables were normalized (converted to Z-scores) prior to model fitting to reduce scaling effects. Models were constructed with up to five predictor variables. Those predictor variables appearing in fitted models that had an adjusted R^2 greater than 0.3 for either species, along with mean annual temperature, annual precipitation, and latitude, were included in subsequent analyses. I then constructed regression models using all combinations of these predictor variables, up to a maximum of three per model, and ranked them by AICc (described below). Table 1 summarizes some of the predictor variables considered, and identifies the variables included in AICc model ranking. For a full list of predictor variables considered, see Appendices A though D. Candidate models were created, fitted, and ranked separately for walleye and white sucker, but models with similar combinations of predictor variables were used for both species.

I assessed the relative importance of the various predictor variables using an information-theoretic approach; fitted models were ranked based on Akaike's Information Criterion (AIC). This provides a means to determine which model or subset of models from a larger set of candidate models can best explain the patterns in the data. Models are ranked based on how well they account for the observed variation in the dependent variable (minimize the Kullback-Leibler distance) relative to their complexity. In general, highly-ranked models are those that can account for a relatively large amount of variability with few parameters (i.e. few predictor variables) (Anderson 2008). The second order information criterion (AICc) adds a greater penalty for model complexity, and is used when sample sizes are small. AICc converges to AIC as the sample size becomes larger and for this reason AICc is used in this study (Anderson 2008).

Model fitting and AICc ranking were conducted twice for each species: once using unadjusted $\delta^{15}N$ and $\delta^{13}C$ in the models, and once using baseline-adjusted $\delta^{15}N$ and $\delta^{13}C$. When conducting AICc ranking, all models must be fitted to the same data set; models fitted on one set of data cannot be compared with models fitted to a smaller subset of the data. Unadjusted fish muscle $\delta^{15}N$ and $\delta^{13}C$ data were available for all of the 70 study lakes, however water chemistry data were only available for 64 of the lakes and ages (used to calculate LGR) were available for 67 of the white sucker populations. The three lakes with missing white sucker age data were not the same as the lakes with missing water chemistry data. For this reason, the AICc ranking of models with unadjusted stable isotope data was conducted with data from 64 walleye lakes and 61 white sucker lakes. The same set of models was then fitted and ranked using baseline-adjusted isotope data from the 28 walleye lakes and 27 white sucker lakes for which baseline isotope and LGR data were available.

In cases where there was no clear 'best model' (indicated by low Akaike weights, w_i), I used full-model averaging. In full-model averaging, conclusions about how each individual predictor variable affects the response variable are based on the entire set of models (Mazerolle 2006, Burnham et al. 2011, Symonds and Moussalli 2011). Weighted model estimates (regression coefficients) and the associated unconditional standard errors were calculated for each variable of interest based on the w_i of the models that included those variables (Burnham 2004). If the 95% confidence limits for a particular variable of interest (calculated as estimate ± (1.96)*unconditional SE, assuming w_i are normally distributed) did not cross 0, I concluded that there was an effect of that variable on [tHg] (Mazerolle 2006). AICc model ranking and model averaging were completed using the AICcmodavg package in R (Mazerolle 2015).

Table 1. Final subset of predictor variables considered in simple and multiple regression analyses to explain [tHg] in walleye and white sucker. Variables included in candidate models used in AICc ranking indicated by *. The symbols are referred to in subsequent tables.

Predictor variables	Units	Symbol
Fish traits (adjusted to standard body size)		
Lifetime growth rate*	mm yr^{-1}	LGR
Body condition*	-	cond
Fish muscle stable carbon isotope ratio*	‰	$\delta^{13}C$
Fish muscle stable nitrogen isotope ratio*	‰	$\delta^{15}N$
Water chemistry		
Lake sulfate concentration*	mg L^{-1}	$[SO_4]$
Dissolved organic carbon concentration*	mg L^{-1}	[DOC]
Dissolved inorganic carbon concentration*	mg L^{-1}	[DIC]
Conductivity*	µS cm^{-1}	conduct
Alkalinity*	mg L^{-1} $CaCO_3$	alk
pH	-	pH
Water chemistry principal component 1*	-	PC 1
Water chemistry principal component 2*	-	PC 2
Water chemistry principal component 4*	-	PC 4
Physical lake and watershed characteristics		
Mean slope of drainage basin*	%	slope
Drainage area to lake area ratio*	-	D_a:L_a
Percent of drainage basin area as wetlands*	%	% wetland
Maximum lake depth*	M	depth
Climate		
Annual mean temperature*	°C	temp
Annual precipitation*	mm	ppt
Growing season length	days	grow
Other		
Latitude*	-	lat

Results

Summary statistics

Walleye had significantly greater [tHg] (paired comparisons t-test; t=13.87, p<0.001, n=70), growth rates (paired comparisons t-test; t=3.98, p<0.001, n=67), and $\delta^{15}N$ (paired comparisons t-test; t=31.29, p<0.001, n=70) relative to white sucker (Fig 2). Walleye [tHg] ranged from 0.33 to 7.31 ppm while that of white sucker ranged from 0.19 to 1.28 ppm (dry weight). The two species did not differ in condition (paired comparisons t-test; t=-0.46, p=0.651, n=70) or $\delta^{13}C$ (paired comparisons t-test; t=1.82, p=0.073, n=70), however muscle $\delta^{13}C$ was more variable among white sucker than walleye populations (Fig. 2).

The 64 lakes for which water chemistry data were available varied in acidity (pH 6.3 - 8.3), organic content (DOC, 2.8 – 24.0 mg/l), and ionic strength (conductivity, 21.2 – 218.0 µS cm^{-1}). Lakes also varied in major ion concentrations (e.g., [SO_4], 0.05 – 8.50 mg L^{-1}; Ca, 2.08 – 35.50 mg L^{-1}; K, 0.10 – 1.04 mg L^{-1}). The first four PCs explained more than 80% of the observed variation in water chemistry (Table 2) but only the first two and the fourth were used in subsequent analyses. PC 1 (41% of variance) tended to reflect buffering capacity, and was negatively related to pH, alkalinity, and major cation concentrations. PC 2 (21% of variance) tended to reflect nutrient status, and was negatively related to measures of N, P, and [DOC] but positively related to [K] and [SO_4]. PC 4 (7% of variance) tended to reflect only silicon (Table 2).

Ratios of drainage basin area to lake area (D_a:L_a) and wetland area to lake area (W_a:L_a) ranged from 2.47 to 20.77 and 0.08 to 6.64, respectively. Additionally, the proportion of the drainage basin composed of wetlands varied greatly, from 1.16 to 76.75%.

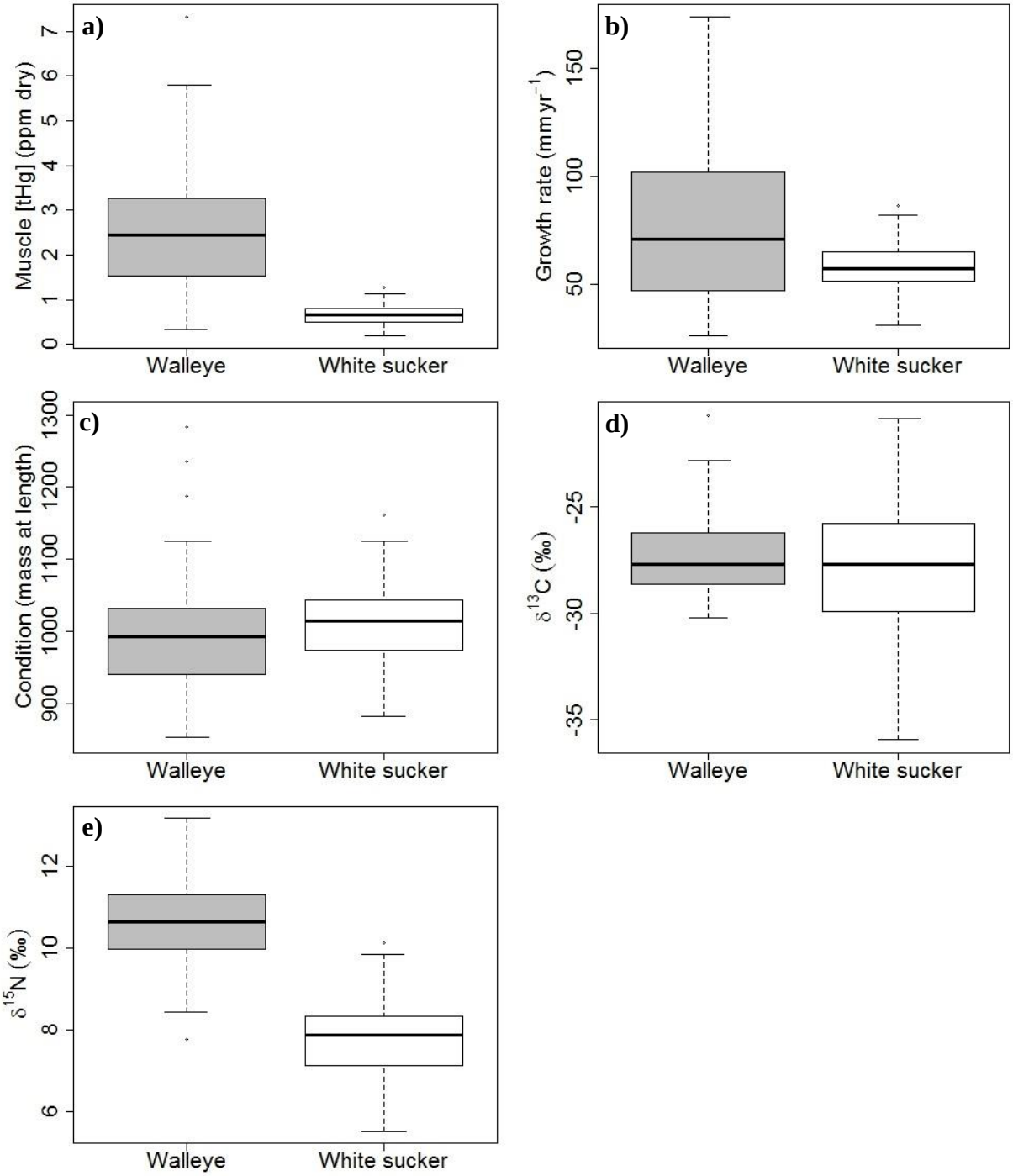

Figure 2. Comparison of walleye and white sucker populations of northern Ontario lakes with respect to a) muscle [tHg], b) growth rate (LGR), c) fish condition (mass at 477 mm and 440 mm for walleye and white sucker, respectively), d) muscle $\delta^{13}C$, and e) muscle $\delta^{15}N$. Summary statistics were based on population means (n = 70, except n = 67 for white sucker LGR) adjusted to 477 and 440 mm TL for walleye and white sucker, respectively. Stable isotope ($\delta^{15}N$, $\delta^{13}C$) values were not baseline-adjusted. Centre lines are medians, box limits are the 25th and the 75th percentiles, and whiskers are ranges excluding populations beyond 1.5 times the interquartile range for the box (depicted as dots).

Table 2. Loadings of the first four principal components (PCs) in a PCA of water chemistry variables for northern Ontario lakes (n=64).

Variable	**PC 1**	**PC 2**	**PC 3**	**PC 4**
Alkalinity	-0.3981*	0.0152	-0.0326	0.0168
Ca	-0.3948*	0.0337	-0.0321	0.0110
Cl	0.0470	0.2988*	0.5266*	-0.1800
Conductivity	-0.3865*	0.1110	0.0846	-0.0338
DIC	-0.3895*	0.0357	-0.0302	0.0542
DOC	-0.0706	-0.4521*	0.1075	-0.0772
K	-0.2538*	0.2429*	0.1540	0.1432
Mg	-0.391*	0.0616	0.0049	0.0153
Na	0.0552	0.3165*	0.5192*	-0.1618
NH_3 and NH_4^+	0.0157	-0.1964	0.4534*	0.1765
Total Kjedahl N	-0.0381	-0.4274*	0.3371*	-0.1813
pH	-0.3607*	-0.0885	0.0596	0.0386
Si	-0.0542	0.0192	-0.1088	-0.8859*
SO_4	0.1477	0.4221*	0.0381	0.1734
Total P	0.0230	-0.3477*	0.2676*	0.1726
Eigenvalue	6.1819	3.1480	2.1433	1.0501
Variance explained (%)	41.21	20.99	14.29	7.00
Sum of variance explained (%)	41.21	62.20	76.49	83.49

* indicates dominant variables within each PC (based on loadings greater than 0.2 or less than -0.2).

Both temperature and precipitation variables followed the expected latitudinal gradient over northern Ontario, with higher temperatures and more precipitation occurring around the more southern lakes. The most southern lake, situated around the same latitude as the town of Parry Sound, experienced the highest mean annual temperature, at 5.5°C, and the highest annual precipitation, at 1123 mm. Conversely, the most northern lake, which is about 100 km south of the Hudson Bay coastline, experienced the lowest mean annual temperature of -3.2°C and the lowest mean annual precipitation, at 515 mm.

Summary statistics for other predictor variables examined in this study are summarized in Appendices A through D.

Concordance between walleye and white sucker

The concordance between fish biology variables between the two species was assessed using a Pearson correlation analysis. Relatively strong, positive correlations were exhibited between walleye and white sucker for muscle [tHg], $\delta^{15}N$, and $\delta^{13}C$ (Fig. 3, Table 3). This suggests that among-lake variation in these variables is strongly influenced by environmental factors that have a similar effect on both species. In contrast, fish growth rates and fish condition did not show strong positive trends between the two species (Fig. 3, Table 3), indicating species-specific or population-specific differences in the response of these traits to environmental factors.

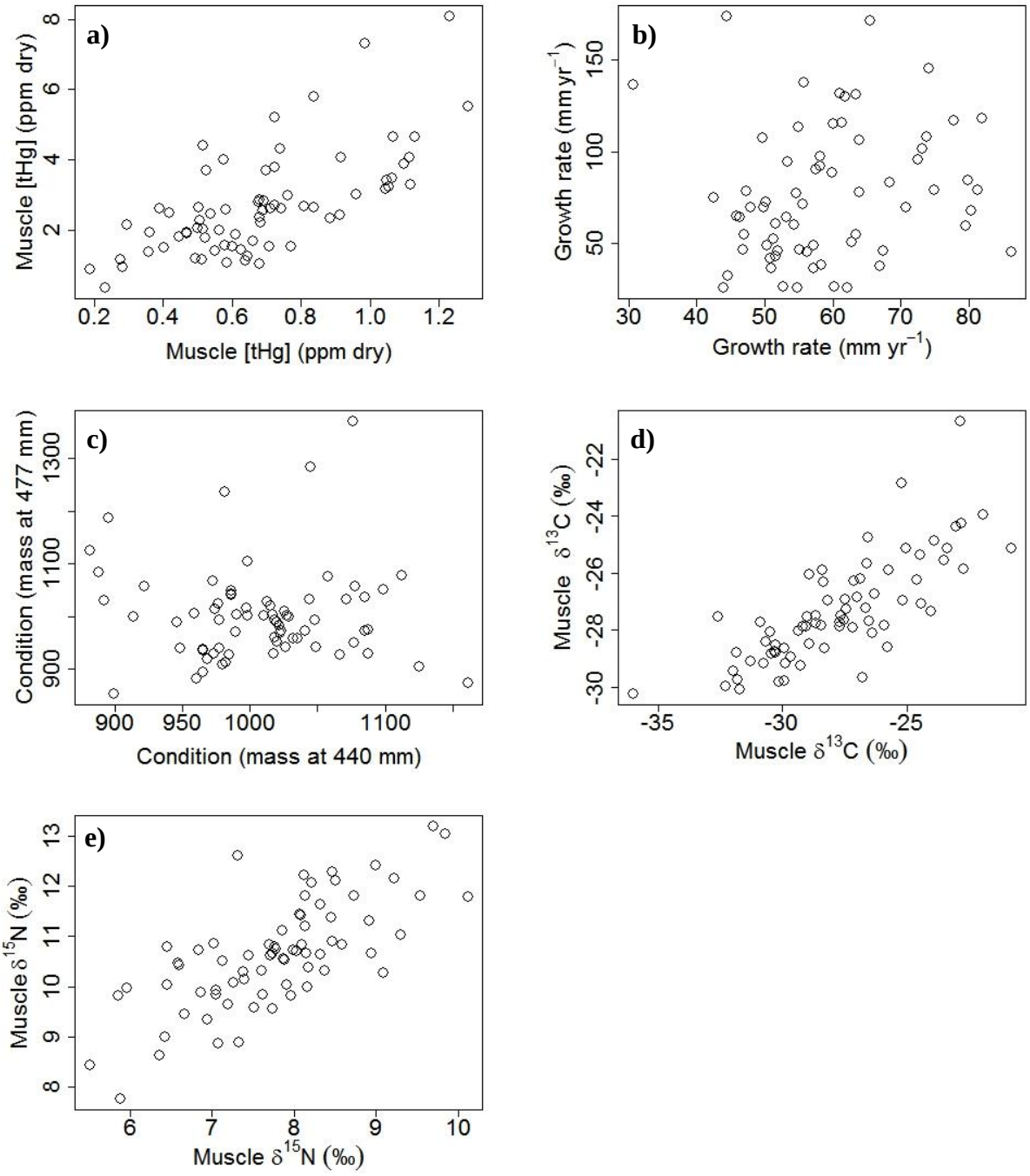

Figure 3. Relationships between walleye (y-axis) and white sucker (x-axis) a) muscle [tHg], b) growth rate, c) fish condition, d) muscle δ^{13}C, and e) muscle δ^{15}N. Symbols are length-adjusted population means (n = 70, except n = 67 for panel b). Isotope ratios were not baseline-adjusted.

Table 3. Pearson correlation matrix for population means of walleye and white sucker muscle total mercury concentration ([tHg]; ppm dry), lifetime growth rates (mm yr^{-1}), body condition, and muscle $\delta^{15}N$ and $\delta^{13}C$ (‰) (from Fig. 3). Fish condition was calculated as predicted fish mass at 477 mm and 440 mm for walleye and white sucker, respectively. Significant correlations are indicated (*p<0.01, **p<0.001).

		Muscle [tHg]		**Growth rate**		**Condition**		**Muscle $\delta^{13}C$**		**Muscle $\delta^{15}N$**	
		WALL	**WS**	**WALL**	**WS**	**WALL**	**WS**	**WALL**	**WS**	**WALL**	**WS**
Muscle [tHg]	**WALL**	1	-	-	-	-	-	-	-	-	-
	WS	0.65**	1	-	-	-	-	-	-	-	-
Growth rate	**WALL**	-0.19	0.13	1	-	-	-	-	-	-	-
	WS	0.02	-0.07	0.16	1	-	-	-	-	-	-
Condition	**WALL**	-0.35*	-0.14	0.58**	-0.12	1	-	-	-	-	-
	WS	0.02	-0.04	-0.35*	0.1	-0.03	1	-	-	-	-
Muscle $\delta^{13}C$	**WALL**	-0.25	-0.16	0.15	0.21	0.1	-0.08	1	-	-	-
	WS	-0.35*	-0.18	0.19	0.06	0.13	-0.15	0.78**	1	-	-
Muscle $\delta^{15}N$	**WALL**	-0.14	-0.22	-0.22	-0.34*	0.08	0.22	-0.32*	-0.32*	1	-
	WS	-0.07	-0.01	-0.1	-0.26	0.09	0.27	-0.41**	-0.4**	0.73	1

Bivariate relationships between muscle [tHg] and predictor variables

Muscle [tHg] appeared to exhibit slightly stronger relationships with fish attributes among walleye populations than among white sucker populations (Fig. 4, Table 4). There were no significant relationships between muscle [tHg] and lifetime growth rate for either species (Fig. 4a,b). Muscle [tHg] was significantly and negatively related to body condition in walleye (Fig. 3c) but not in white sucker (Fig. 4d). Muscle [tHg] was negatively related to non-baseline-adjusted $\delta^{13}C$ in both species, and this relationship was significant for walleye (Fig. 4e,f). This suggests that mercury bioaccumulation is higher in lakes where they consume a more pelagic diet. However, when this relationship was re-examined using baseline-adjusted $\delta^{13}C$ (n = 28 walleye lakes; n = 27 white sucker lakes) it was not statistically significant for either species. Neither walleye nor white sucker [tHg] was significantly related to unadjusted $\delta^{15}N$ (Fig. 4g,h) or adjusted $\delta^{15}N$ across the study lakes.

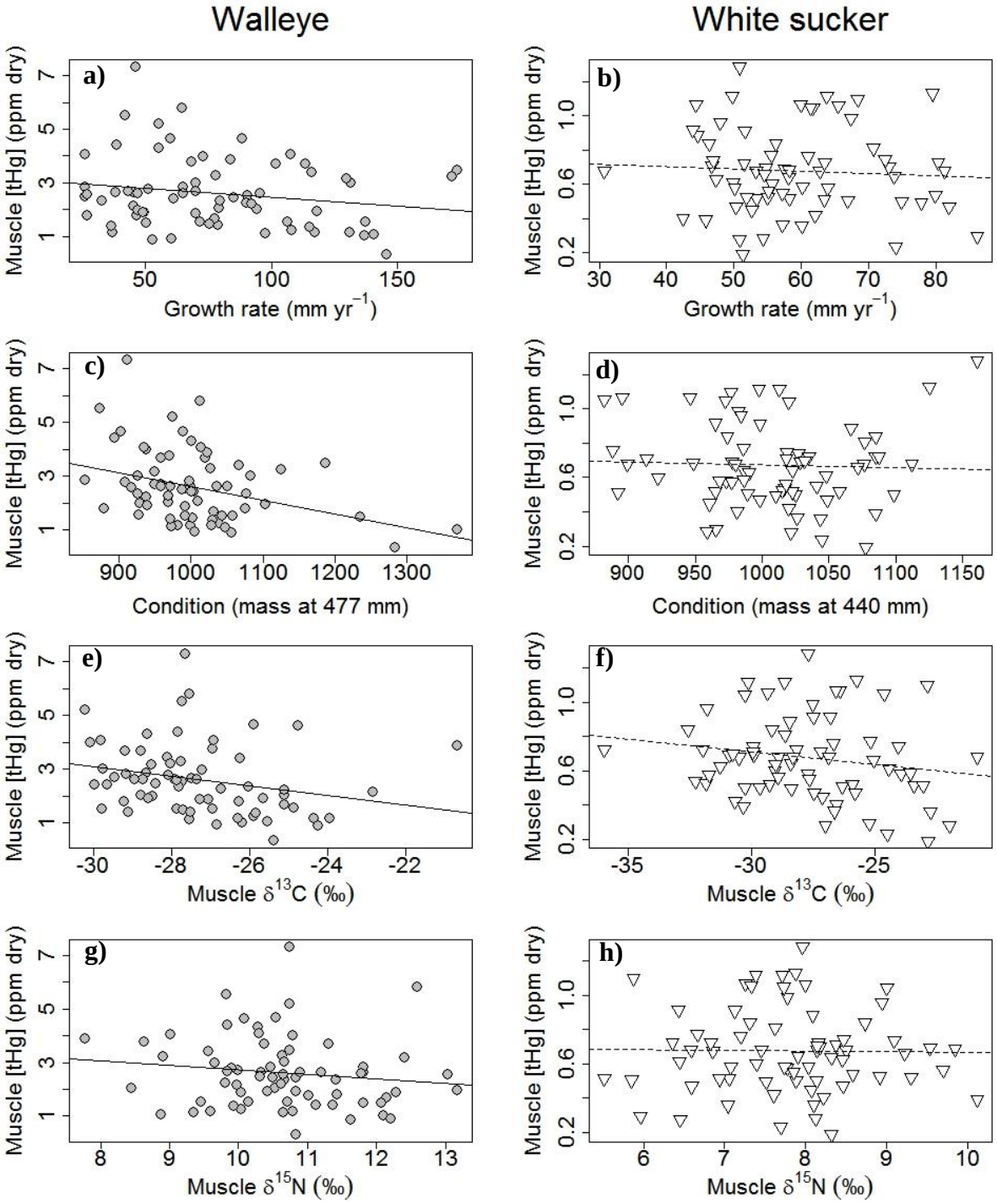

Figure 4. Relationships between muscle [tHg] and fish attributes of walleye (left, grey circles and solid line) and white sucker (right, white triangles and dotted line) in northern Ontario lakes. Plots are for a-b) lifetime growth rate (LGR), c-d) body condition, e-f) muscle δ^{13}C, and g-h) muscle δ^{15}N. Symbols are length-adjusted population means (n = 70, except n = 67 for panel b) and fitted lines are least-squares regressions (statistics summarized in Table 4). Isotope ratios were not baseline-adjusted.

Table 4. Statistics for least-squares regressions of muscle total mercury concentration ([tHg]; ppm dry) against lifetime growth rate (mm yr^{-1}), body condition, and muscle $\delta^{13}C$ and $\delta^{15}N$ (‰) for populations of walleye and white sucker (from Fig. 4). Fish condition was calculated as predicted fish mass at 477 mm and 440 mm for walleye and white sucker, respectively.

Response variable	**Predictor variable (effect)**	**F**	**Error df**	**p**	**R^2**
Walleye muscle [tHg]	LGR (-)	2.43	68	0.124	0.03
	Condition (-)	9.33	68	0.003*	0.12
	$\delta^{13}C$ (-)	4.40	68	0.004*	0.06
	$\delta^{15}N$ (-)	1.33	68	0.253	0.02
White sucker muscle [tHg]	LGR (-)	0.28	65	0.599	0.00
	Condition (-)	0.11	68	0.741	0.00
	$\delta^{13}C$ (-)	2.23	68	0.140	0.03
	$\delta^{15}N$ (-)	0.01	68	0.911	0.00

* significant at $p < 0.05$

Relationships between muscle [tHg] and water chemistry variables appeared to be somewhat stronger than those associated with growth rate, body condition or other fish attributes for both walleye and white sucker. The relationship between muscle [tHg] and PC1 was positive and statistically significant for both species (Fig. 5), indicating that fish [tHg] was inversely related to waterbody buffering capacity. Muscle [tHg] was not significantly related to water chemistry PC2, PC3 or PC4 for either species. Relationships between muscle [tHg] and water chemistry were examined further with selected variables. The relationship between muscle [tHg] and water [SO_4] was best explained by a quadratic function, with the highest muscle [tHg] found in fish populations of lakes with [SO_4] of 3 – 4 mg L^{-1}, and this relationship was significant for both species (Fig. 6a,b). Consistent with the PC1 trends, walleye and white sucker muscle [tHg] were negatively related to both lake pH (Fig. 5c,d) and conductivity (Fig. 6e,f). Finally, the relationship between muscle [tHg] and water [DOC] was also best explained by a quadratic function. The highest muscle [tHg] were found in walleye and white sucker populations of lakes with [DOC] of about 12 mg L^{-1} and 9 mg L^{-1}, respectively (Fig. 6g,h). This relationship was only significant for walleye.

Mercury levels in fish also appeared to be related to some physical characteristics of the drainage basins. Walleye and white sucker muscle [tHg] were positively and significantly correlated with both mean drainage basin slope (Fig. 7a,b) and D_a:L_a (Fig. 7c,d). The relationship between muscle [tHg] and percent wetland in the watershed was negative for both species, although only statistically significant for white sucker (Fig. 7e,f). Neither walleye nor white sucker muscle [tHg] were significantly correlated with maximum lake depth (Fig. 7 g,h).

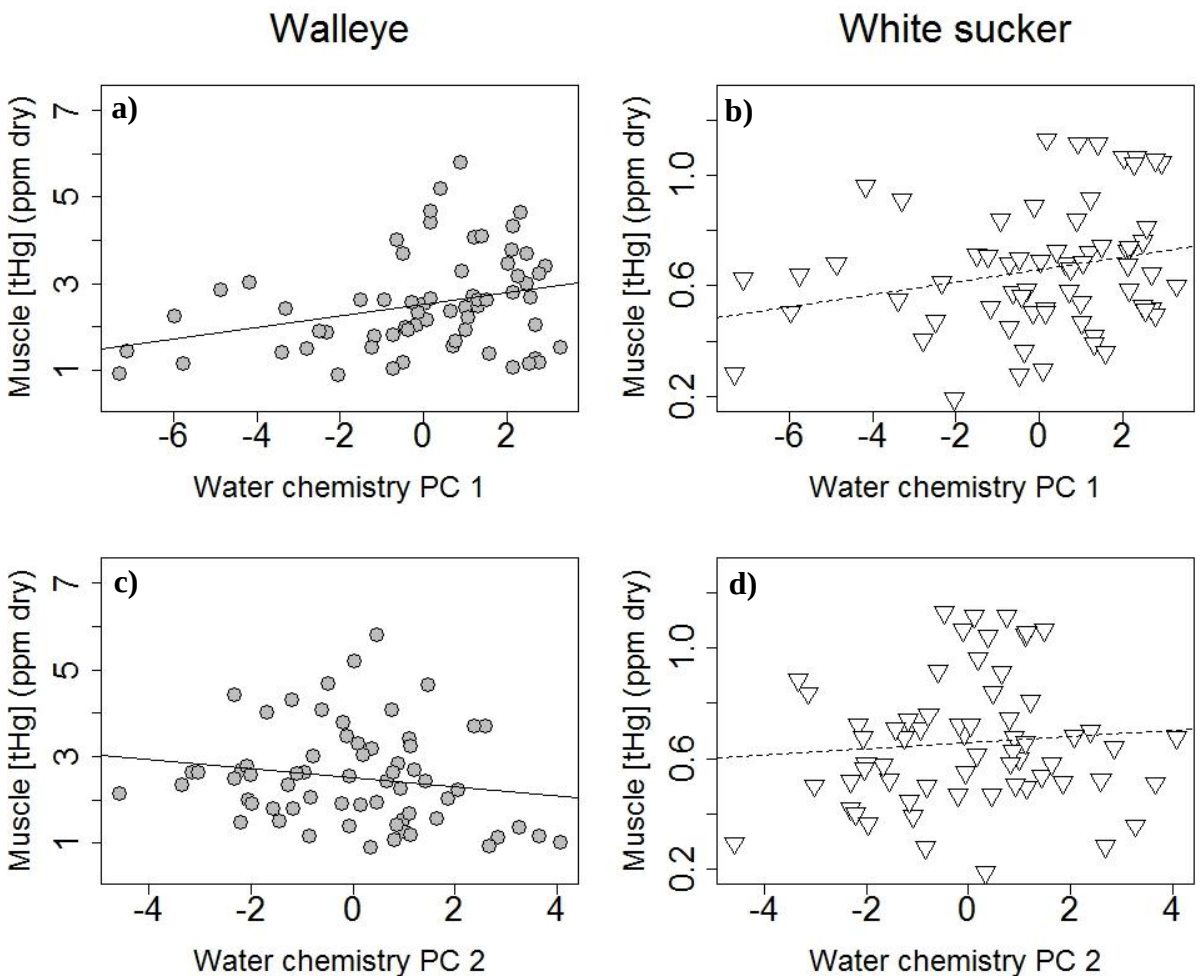

Figure 5. Relationships between muscle [tHg] and the first two principal components (PC) of water chemistry for walleye (left, grey circles and solid line) and white sucker (right, white triangles and dotted line) in northern Ontario lakes; a) higher PC1 indicates lower pH, conductivity, major cation concentrations, and alkalinity, b) higher PC 2 indicates higher [K] and [SO_4] and lower [total P] and [DOC] (Table 1). Symbols are length-adjusted population means (n = 64) and fitted lines are least-squares regressions (statistics summarized in Table 5).

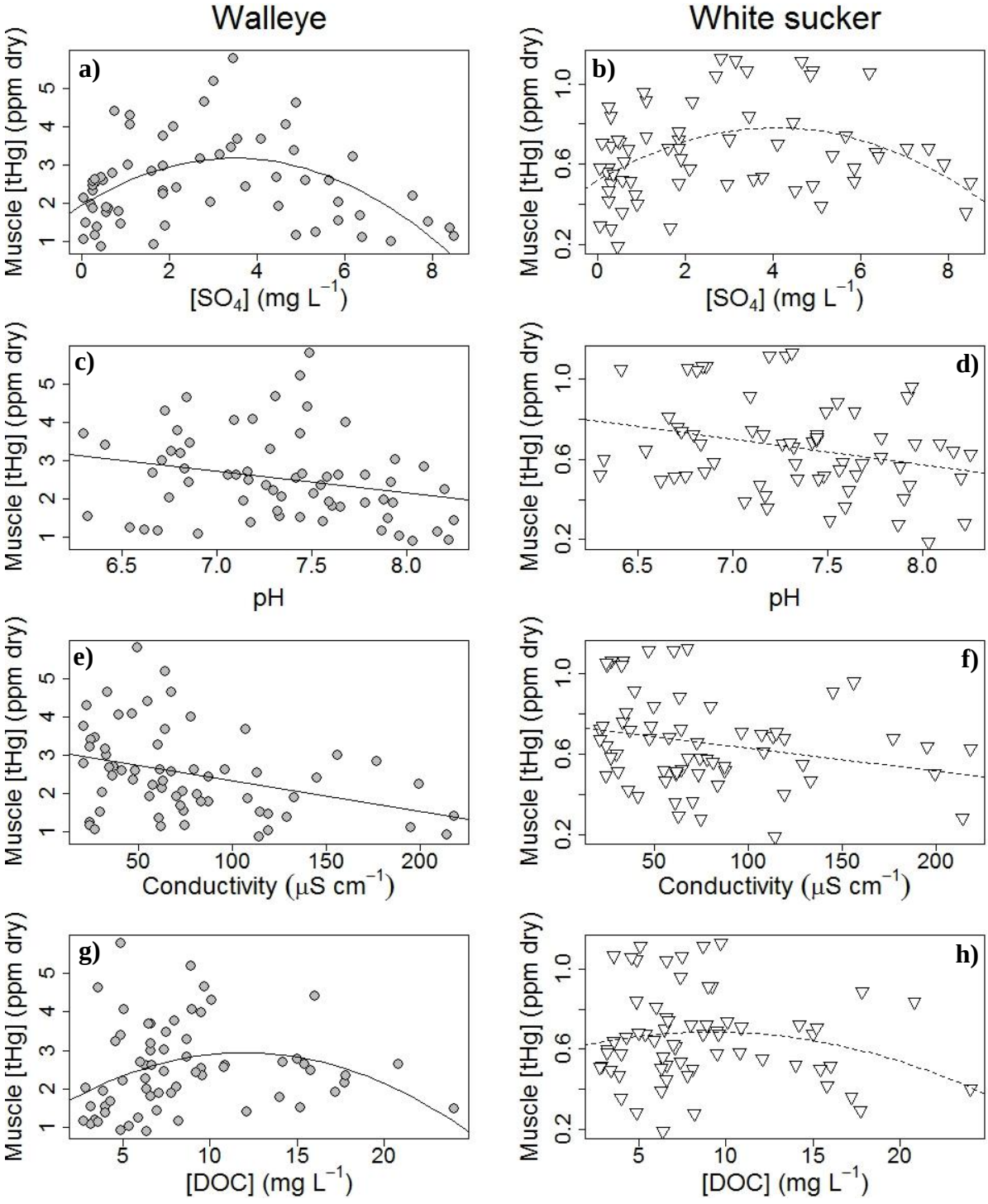

Figure 6. Relationships between muscle [tHg] and selected water chemistry variables for walleye (left, grey circles and solid line) and white sucker (right, white triangles and dotted line) in northern Ontario lakes. Plots are for a-b) sulphate concentration [SO_4], c-d) pH, e-f) conductivity, and g-h) dissolved organic carbon concentration ([DOC]). Symbols are length-adjusted population means (n = 64) and fitted lines are least-squares regressions (statistics summarized in Table 5).

Table 5. Statistics for least-squares regressions of walleye and white sucker muscle total mercury concentration ([tHg]; ppm dry) against various water chemistry parameters (from Figs. 5 and 6). All are simple linear models, except [SO_4] and [DOC] which are quadratic models.

Response variable	**Predictor variable (effect)**	**F**	**Error df**	**p**	**R^2**
Walleye muscle [tHg]	PC 1 (+)	6.24	62	0.015*	0.09
	PC 2 (-)	1.77	62	0.188	0.03
	[SO_4] (+), [SO_4]^2 (-)	10.6	61	< 0.001*	0.23
	pH (-)	4.26	62	0.043*	0.06
	Conductivity (-)	8.65	62	0.005*	0.12
	[DOC] (+), [DOC]^2 (-)	3.24	61	0.046*	0.07
White sucker muscle [tHg]	PC 1 (+)	4.26	62	0.043*	0.06
	PC 2 (+)	0.48	62	0.493	0.01
	[SO_4] (+), [SO_4]^2 (-)	6.58	61	0.003*	0.15
	pH (-)	5.42	62	0.023*	0.08
	Conductivity (-)	4.05	62	0.048*	0.06
	[DOC] (+), [DOC]^2 (-)	1.13	61	0.362	0.00

* significant at $p < 0.05$

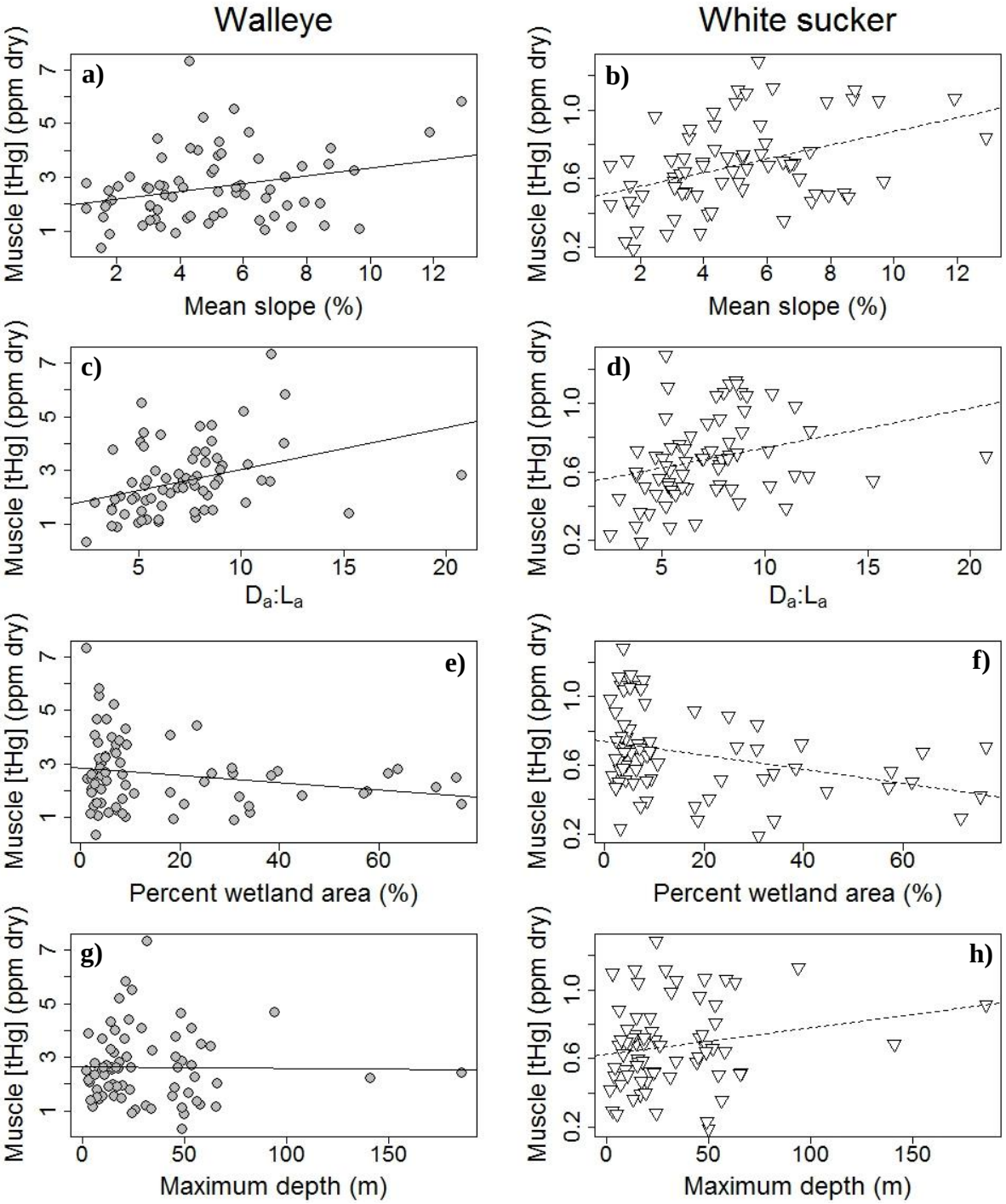

Figure 7. Relationships between muscle [tHg] and selected drainage basin physical characteristics for walleye (left, grey circles and solid line) and white sucker (right, white triangles and dotted line) in northern Ontario lakes. Plots are for a-b) mean slope of the drainage basin, c-d) drainage basin area to lake area ratio (D_a:L_a), e-f) percent of drainage basin area as wetlands, and g-h) lake maximum depth. Symbols are length-adjusted population means (n = 70, except n = 64 for maximum depth) and fitted lines are least-squares regressions (statistics summarized in Table 6).

Table 6. Statistics for least-squares regressions of walleye and white sucker muscle total mercury concentration ([tHg]; ppm dry) against the following watershed and lake physical characteristics: mean slope of drainage basin, drainage basin area to lake area ratio (D_a:L_a), percent drainage basin as wetlands, and lake maximum depth (from Fig. 7).

Response variable	**Predictor variable (effect)**	**F**	**Error df**	**p**	**R^2**
Walleye muscle [tHg]	slope (+)	5.84	68	0.018*	0.08
	Da:La (+)	9.71	68	0.003*	0.13
	% wetland (-)	2.87	68	0.095	0.04
	depth (-)	0.01	68	0.926	0.00
White sucker muscle [tHg]	Mean slope (+)	14.2	68	< 0.001*	0.17
	Da:La (+)	5.95	68	0.017*	0.08
	% wetland (-)	8.90	68	0.004*	0.12
	depth (+)	2.66	68	0.108	0.04

* significant at $p < 0.05$

Relationships between mercury in fish and climatic variables tended to exhibit curvilinear trends, and a quadratic model often fit the data best, particularly with variables related to temperature (Table 7). Muscle [tHg] increased from south to north up to about 49° N, then gradually decreased beyond (Fig. 8a,b). Similarly, muscle [tHg] peaked at a growing season of about 180 days (Fig. 8c,d) and a mean annual temperature of about 2.5°C (Fig. 8e,f). The same quadratic relationships were seen when muscle [tHg] was regressed against other temperature-related variables, such as minimum and maximum temperatures during the coldest and warmest periods, and GDD (not shown). However, the relationship between muscle [tHg] and GDD was not statistically significant for either fish species. In contrast, the relationships between muscle [tHg] and annual precipitation were best represented by linear models; these relationships were weakly positive but not statistically significant for either species (Fig. 8g,h).

Some of the variables considered did not exhibit a discernable relationship with [tHg] in either species, and were thus not included in subsequent analyses. These variables include, but are not limited to secchi depth, lake surface area, and the two anoxia factors (AF_{TN} or AF_{TP}).

Latitudinal gradients in other predictor variables

In addition to fish [tHg] and climatic variables, several of the other predictor variables of interest, both biotic and abiotic, exhibited distinct latitudinal trends (Table 8). Lifetime growth rate declined significantly from south to north in both walleye and white sucker, though the trend was much stronger in the former (Fig. 9a,b). Body condition also declined significantly from south to north in walleye, but there was no significant trend in white sucker (Fig. 9c,d). In terms of lake chemistry, [SO_4] exhibited a strong declining trend from south to north (Fig. 9e), whereas pH and [DOC] both increased from south to north (Fig. 9f,g).

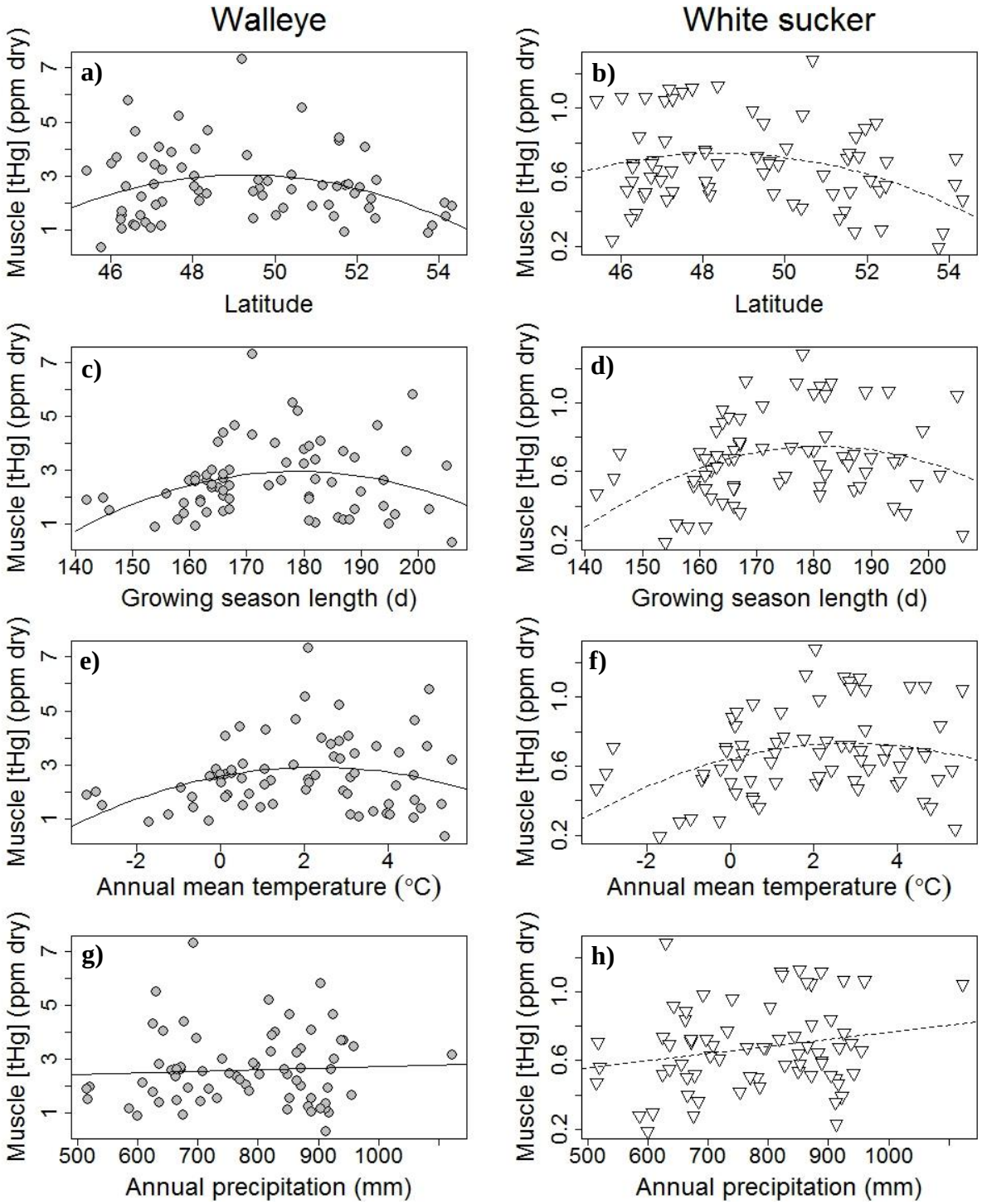

Figure 8. Relationships between muscle [tHg] and selected spatial and climatic gradients for walleye (left, grey circles and solid line) and white sucker (right, white triangles and dotted line) in northern Ontario lakes. Plots are for a-b) latitude, c-d) length of annual growing season, e-f) annual mean air temperature, and g-h) annual precipitation. Symbols are length-adjusted population means (n = 70) and fitted lines are least-squares regressions (statistics summarized in Table 7).

Table 7. Statistics for least-squares regressions of walleye and white sucker muscle total mercury concentration ([tHg]; ppm dry) against latitude and various climatic variables (from Fig. 8). All models were quadratic except simple linear for annual precipitation.

Response variable	**Predictor variable (effect)**	**F**	**Error df**	**p**	**R^2**
Walleye muscle [tHg]	lat (+), lat^2 (-)	3.43	67	0.038*	0.07
	grow (+), $grow^2$ (-)	3.28	67	0.044*	0.06
	temp (+), $temp^2$ (-)	3.19	67	0.048*	0.06
	ppt	0.23	68	0.63	0.00
White sucker muscle [tHg]	lat (+), lat^2 (-)	3.94	67	0.024*	0.08
	grow (+), $grow^2$ (-)	4.39	67	0.016*	0.09
	temp (+), $temp^2$ (-)	4.12	67	0.021*	0.08
	ppt	3.42	68	0.069	0.05

* significant at $p < 0.05$

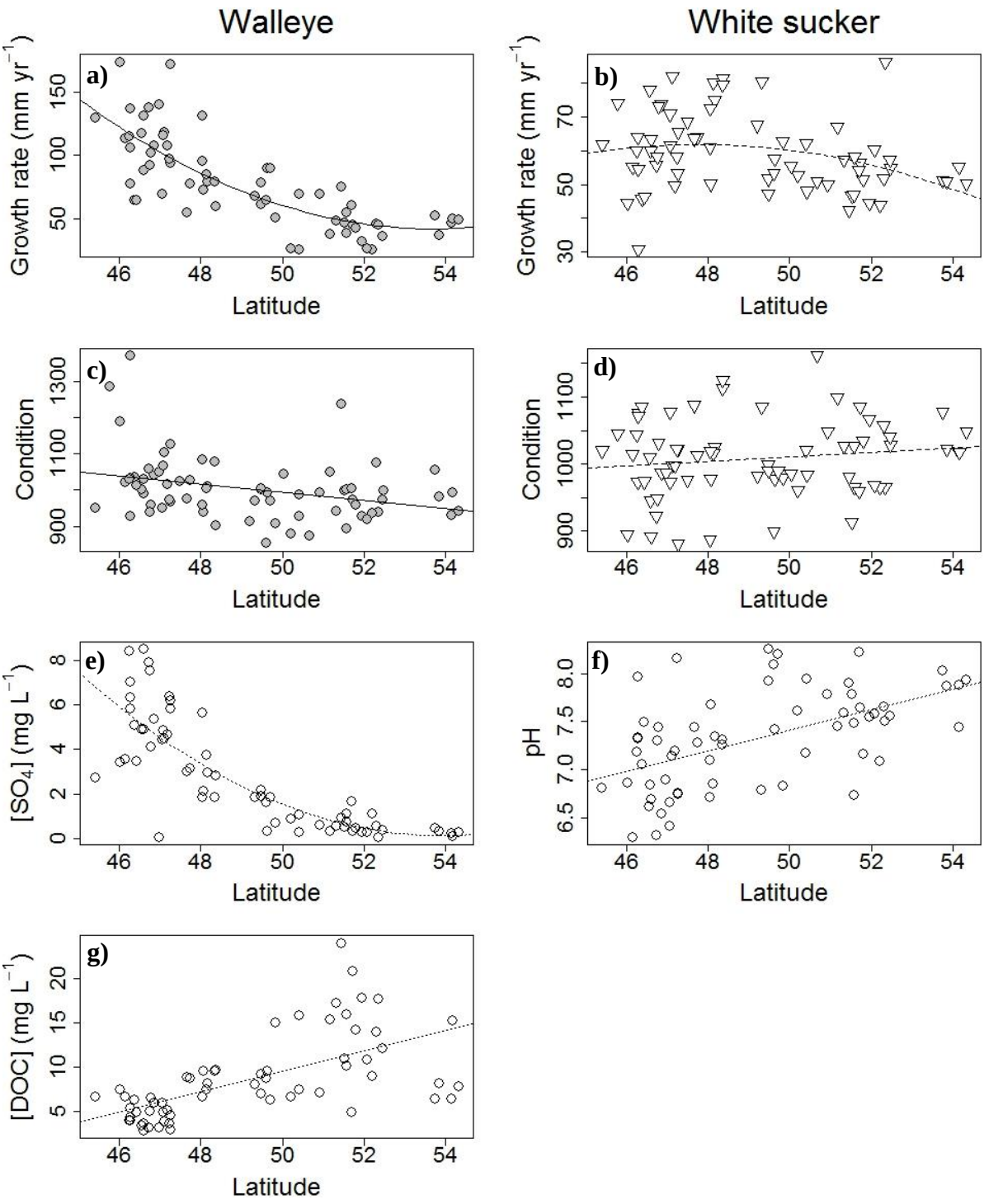

Figure 9. Latitudinal gradients in various biotic and abiotic variables in northern Ontario lakes. a-b) lifetime growth rate (LGR) of walleye (left, grey circles and solid line, n =70) and white sucker (right, white triangles and dotted line, n = 67), c-d) body condition of walleye (left, grey circles and solid line, n =70) and white sucker (right, white triangles and dotted line, n = 70), e) sulphate concentration [SO_4] (n = 65), f) pH (n = 64), and g) dissolved organic carbon concentration [DOC] (n = 64). Symbols are (a-d) length-adjusted population means, or lake means (e-g) and fitted lines are least-squares regressions (statistics summarized in Table 8).

Table 8. Statistics for least-squares regressions of various biotic and abiotic variables against latitude for northern Ontario lakes (from Fig. 9). Models were quadratic for walleye and white sucker growth rate and [SO_4], and simple linear for all others.

Response variable (trend)	**F**	**Error df**	**p**	**R^2**
Walleye LGR (-)	60.2	67	< 0.001*	0.63
White sucker LGR (-)	3.37	64	0.041*	0.07
Walleye condition (-)	7.75	68	0.007*	0.10
White sucker condition (+)	1.55	68	0.217	0.02
[SO_4] (-)	64.7	61	< 0.001*	0.67
pH (+)	25.1	62	< 0.001*	0.29
[DOC] (+)	37.6	62	< 0.001*	0.38

AICc and multimodel inference

Predictor variables selected for inclusion in model building and AICc ranking were generally those that exhibited strong relationships with either walleye or white sucker muscle [tHg] in the preceding analyses. When correlated predictor variables exhibited similar trends with muscle [tHg], the predictor variable that explained less variability was excluded to minimize multicollinearity. For example, many of the temperature-related climate variables were strongly correlated with each other and exhibited similar relationships with walleye and white sucker muscle [tHg]. Mean annual temperature was the only temperature-related climate variable included in the candidate models because it best predicted muscle [tHg] for both species. Certain water chemistry parameters had significant relationships with either walleye or white sucker [tHg] and consequently were included in candidate regression models, even though they were also represented in the principal components. If an individual chemical variable was a strong contributor to a chemistry principal component, the two were never included in the same model. Table 1 summarizes the final subset of predictor variables included in the modeling exercise. For each species, a total of 822 models with up to three predictor variables (a predictor variable entering in quadratic form was still considered as a single variable) were fitted by least-squares simple and multiple regression and ranked by AICc. The same set of models (i.e., same combinations of predictor variables) was used for both species.

For walleye muscle [tHg], the five highest ranking models overall, and the highest ranking one, two, and three variable models are summarized in Table 9. A model that included [DOC], watershed slope and fish condition received the most support, with an Akaike weight of 0.35 (Table 9). The second ranking model, in which muscle [tHg] is a function of [SO_4], [DOC] and mean watershed slope was marginally less well-supported, with an Akaike weight of 0.26 (Table

9). The top ranking model was only 1.3 times better than the next highest-ranking model (based on an evidence ratio of Akaike weights: 0.35/0.26), and the low Akaike weight suggests that it is unlikely to be the 'true model' (based on $w_i = 0.35$; Table 9). Top ranking models included variables representing water chemistry, watershed characteristics, and fish traits but not latitude or climate. No one or two predictor models ranked highly; all one and two variable models had Akaike weights equal to or less than 0.01.

Model averaging indicated that of the 18 predictor variables considered in the candidate models, 13 were determined to have effects on walleye [tHg], as the 95% confidence intervals of their regression coefficients excluded 0 (Table 10). Variables having an effect were walleye body condition, muscle $\delta^{13}C$, the quadratic functions of [SO_4] and [DOC], chemistry PCs 1, 2, and 4, [DIC], alkalinity, conductivity, mean watershed slope, and D_a:L_a. None of the confidence intervals for coefficients of the climate-related variables excluded 0 (Table 10).

When the walleye analysis was repeated using the smaller subset of data (n = 28 lakes) with baseline-adjusted $\delta^{13}C$, the top ranking models were slightly different than those seen using a greater data set using unadjusted isotope data. For example, the top ranking model included PC1, the quadratic function of [SO_4], and condition (w_i=0.15). The third, fourth and fifth top-ranking models contained muscle $\delta^{13}C$ (not shown). However, these models had very little likelihood of being 'true' models ($w_i \leq 0.1$). The presence of $\delta^{13}C$ in these top ranking models when using baseline-adjusted walleye muscle isotope data might indicate that walleye [tHg] was influenced by inter-population variation in feeding ecology such that fish populations that had greater contributions of benthic carbon in their diet had greater mercury (indicated by the positive effect of baseline adjusted $\delta^{13}C$ on walleye [tHg]; results not shown). The extremely

low model weights suggest that this is unlikely, nevertheless. Again, no climate variables were present in the top ranking models.

We additionally ran the AICc ranking using models including baseline adjusted $\delta^{15}N$. The top ranking models were not altered with the addition of baseline adjusted $\delta^{15}N$, thus confirming that neither adjusted nor unadjusted $\delta^{15}N$ had an effect on walleye [tHg].

Table 9. Selected linear models relating walleye muscle [tHg] to various predictor variables. Displayed values are the model rank, second order Akaike Information Criterion (AICc), Akaike differences (ΔAICc), Akaike weights (w_i), and adjusted R^2 (Adj. R^2). Models are ranked from lowest to highest AIC_c values. The direction of the predictor variable effect is indicated in parentheses. Stable isotope values ($\delta^{13}C$) used in these models were not baseline-adjusted. Models were fit to data of 64 lakes. Model variables are defined in Table 1.

Predictor variables in model (effect)	**Rank**	**AICc**	**ΔAICc**	**w_i**	**Adj. R^2**
[DOC] (+), $[DOC]^2$ (-), slope (+), cond (-)	1	166.73	0	0.35	0.45
$[SO_4]$ (+), $[SO_4]^2$ (-), [DOC] (+), $[DOC]^2$ (-), slope (+)	2	167.32	0.59	0.26	0.46
PC4 (+), [DOC] (+), $[DOC]^2$ (-), slope (+)	3	168.66	1.93	0.13	0.43
PC1 (+), $[SO_4]$ (+), $[SO_4]^2$ (-), D_a:L_a (+)	4	170.63	3.91	0.05	0.42
[DOC] (+), $[DOC]^2$ (-), slope (+), $\delta^{13}C$ (-)	5	171.40	4.68	0.03	0.41
[DOC] (+), $[DOC]^2$ (-), slope (+)	8	173.55	6.82	0.01	0.38
PC1 (+), $[SO_4]$ (+), $[SO_4]^2$ (-)	24	176.61	9.89	0.00	0.35
$[SO_4]$ (+), $[SO_4]^2$ (-)	135	185.47	18.74	0.00	0.23
D_a:L_a (+)	345	190.85	24.13	0.00	0.15
lat (+), lat^2 (-)	729	199.44	32.72	0.00	0.05
temp (+), $temp^2$ (-)	730	199.55	32.82	0.00	0.04
ppt (+)	735	199.83	33.11	0.00	0.02

Table 10. Model-averaged estimates for parameters of interest based on AICc model ranking for walleye muscle [tHg] regression models. $\delta^{13}C$ values used in these models were not baseline adjusted.

Variable	Model-averaged parameter estimate	Unconditional SE
LGR	-0.38	0.21
cond*	-0.35	0.12
$\delta^{13}C$*	-0.31	0.15
PC 1*	0.39	0.14
PC 2*	-0.37	0.18
PC 4*	0.32	0.13
$[SO_4]$	0.36	0.22
$[SO_4]^2$*	-0.47	0.14
[DOC]*	1.06	0.24
$[DOC]^2$*	-0.44	0.12
[DIC]*	-0.41	0.15
alka*	-0.41	0.16
conduct*	-0.41	0.13
slope*	0.80	0.21
D_a:L_a*	0.31	0.13
% wetland	-0.15	0.18
depth	0.04	0.14
temp	0.29	0.22
$temp^2$	-0.01	0.12
ppt	0.21	0.21
lat	-0.07	0.31
lat^2	-0.12	0.18

* Indicates parameters for which 0 is excluded from the 95% confidence interval and that the variable influences mercury accumulation.

For white sucker muscle [tHg], the five highest ranking models overall, and the highest ranking one, two, and three variable models are summarized in Table 11. Similar to walleye, top-ranking white sucker models included variables representing water chemistry, watershed characteristics, and fish traits, but not latitude or mean annual temperature. Precipitation is present in the third ranking model, however the results of the multi model averaging (discussed below) indicates that despite being in a top ranking model, it does not have an effect on white sucker [tHg]. The white sucker models were dominated more by watershed characteristics than by water chemistry or fish traits (Table 11). The top- ranking white sucker model, which included drainage basin slope, maximum lake depth, and muscle $\delta^{13}C$, had an Akaike weight of 0.24 and was 6 times better than the second place model (based on an evidence ratio of Akaike weights: 0.24/0.04). The second-ranking model included lake conductivity, mean drainage basin slope, and D_a:L_a (Table 11).

Multimodel inference indicated that of the 18 variables considered in building the white sucker models, muscle $\delta^{13}C$, lake [DOC], mean drainage basin slope, D_a:L_a, percent wetland in the watershed, and maximum lake depth had significant effects on white sucker [tHg] accumulation, as the 95% confidence intervals of their regression coefficients excluded 0 (Table 12). As with walleye, none of the climate-related variables appeared to affect white sucker [tHg].

Fitting and ranking these models on the subset of 27 lakes with baseline-adjusted isotope data altered the model rank. Top ranking models contained some of the same variables identified in the analysis of the larger data set, but annual precipitation, lake [SO_4], lake [DOC], and white sucker growth rate also appeared to rise in model ranking (not shown). However the top ranking model, which included precipitation and the quadratic function of [DOC], had an Akaike weight

of only 0.01, and was thus very unlikely to represent the actual relationship predicting white sucker [tHg]. Neither baseline adjusted $\delta^{13}C$ nor $\delta^{15}N$ rose to the top.

Table 11. Selected linear models relating white sucker muscle [tHg] to various predictor variables. Displayed values are the model rank, second order Akaike Information Criterion (AICc), Akaike differences (ΔAICc), Akaike weights (w_i), and adjusted R^2 (Adj. R^2). Models are ranked from lowest to highest AIC_c values. The direction of the predictor variable effect is indicated in parentheses. Stable isotope values ($\delta^{13}C$) used in these models were not baseline-adjusted. Models were fit to data of 61 lakes. Model variables are defined in Table 1.

Predictor variables in model (effect)	**Rank**	**AICc**	**ΔAICc**	**w_i**	**Adj. R^2**
slope (+), depth (+), $\delta^{13}C$ (-)	1	-24.90	0	0.24	0.35
conduct (-), slope (+), D_a:L_a (+)	2	-21.37	3.54	0.04	0.26
ppt (+), [DOC] (+), $[DOC]^2$ (-), slope (+)	3	-21.26	3.64	0.04	0.32
slope (+), D_a:L_a (+), depth (+)	4	-20.97	3.94	0.03	0.30
conduct (-), depth (+), $\delta^{13}C$ (-)	5	-20.91	3.99	0.03	0.30
[DOC] (+), $[DOC]^2$ (-), slope (+)	11	-19.72	5.19	0.02	0.29
slope (+), D_a:L_a (+)	13	-19.57	5.34	0.02	0.27
slope (+)	78	-14.94	9.97	0.00	0.20
$[SO_4]$ (+), $[SO_4]^2$ (-)	224	-11.29	13.62	0.00	0.17
ppt (+)	333	-9.66	15.24	0.00	0.13
lat (-), lat^2 (-)	413	-8.47	16.44	0.00	0.13
temp (+), $temp^2$ (-)	478	-7.63	17.27	0.00	0.11

Table 12. Model-averaged estimates for parameters of interest based on AICc model ranking for white sucker regression models. $\delta^{13}C$ values used in these models were not baseline adjusted.

Variable	Model-averaged estimate	Unconditional SE
LGR	-0.03	0.03
cond	-0.01	0.03
$\delta^{13}C$	-0.09	0.03
PC 1	0.04	0.04
PC 2	-0.04	0.04
PC 4	0.00	0.04
$[SO_4]$	0.03	0.06
$[SO_4]^2$	-0.07	0.04
[DOC]*	0.13	0.05
$[DOC]^2$*	-0.06	0.02
[DIC]	-0.05	0.04
alk	-0.04	0.05
conduct	-0.05	0.03
slope*	0.10	0.04
D_a:L_a*	0.07	0.03
% wetland*	-0.08	0.04
depth*	0.09	0.04
temp	0.02	0.05
$temp^2$	-0.03	0.03
ppt	0.06	0.04
lat	-0.03	0.07
lat^2	-0.03	0.04

* Indicates parameters for which 0 is excluded from the 95% confidence interval and that the variable influences mercury accumulation.

Discussion

The aim of this study was to investigate how climate influences the accumulation of mercury in walleye and white sucker in northern Ontario lakes. The results of my model-building and ranking show that neither walleye nor white sucker mercury concentrations were strongly related to climatic variables, but instead by a combination of the following: water chemistry, muscle $\delta^{13}C$, drainage basin characteristics, fish condition (walleye only) and maximum lake depth (white sucker only). Bivariate regression analysis similarly showed that mercury in walleye and white sucker was not strongly driven by any one predictor variable, but was weakly related to many of the variables investigated, including some weak but statistically significant curvilinear relationships with some climate variables.

I predicted an overall trend of increasing fish [tHg] across a climatic gradient from south to north in Ontario. Contrary to my prediction, I observed a modest, but significant curvilinear relationship between muscle [tHg] and various temperature-related climate variables (e.g., latitude, growing season length, annual mean temperature); muscle [tHg] in both walleye and white sucker increased moving north to about 49° latitude and decreased thereafter. In contrast, neither walleye nor white sucker [tHg] showed significant relationships with precipitation patterns; though precipitation did appear in the third top ranking model predicting white sucker [tHg], the results of the model averaging did not show precipitation to have an effect. By modeling fish [tHg] with respect to these climate variables, as well as numerous other variables purported to influence fish [tHg] across the northern Ontario landscape, I demonstrated that climate effects appear to be relatively weak compared to other factors.

This study is unique in that it included two trophically distinct species, covered a large geographic area, and included a wide variety of predictor variables. Recently Lucotte et al. (2016) investigated climatic and landscape effects on mercury accumulation in walleye and northern pike in northern Quebec. Like the current study, Lucotte et al. (2016) modelled fish mercury with respect to environmental characteristics across 90 lakes spanning a similar range of latitudes using a stepwise multiple linear regression approach. Their results showed that fish growth and certain watershed variables explained most of the variation in mercury concentrations among populations, and that latitude and mean winter temperature were significant predictors of walleye [tHg] and annual temperature was a predictor of northern pike [tHg]. Their results indicate that walleye and northern pike in colder and northern climates generally have greater [tHg], consistent with my predictions but not my results. Despite using a similar approach and latitudinal range, my results differed from those of Lucotte et al. (2016) in that I found no climate variables to be strong predictors of fish [tHg]. However, my analyses included a greater diversity of predictor variables, and the models that ranked highly also tended to contain a diversity of predictor variables. In my Ontario data set, fish [tHg] showed curvilinear relationships with temperature variables, but the modelling exercise demonstrated that watershed, lake, and fish biology variables were stronger predictors overall.

Field studies conducted in different North American locations have similarly looked at the relationships between mercury concentrations in top predatory fishes and various environmental factors (e.g., McMurtry et al. 1989, Rypel 2010, Mattieu et al. 2013). Research on mercury in lower trophic-level fish species, such as white sucker, is less common, because they are not as frequently consumed by humans and because they usually contain lower mercury concentrations, and thus pose less of a threat to human health. Indeed, most contaminant monitoring in Ontario

focusses on piscivorous species (Sandstrom et al. 2010). I chose to study two species of fish that occupy different trophic positions: a piscivore and a benthivore. My results show that mercury levels in these two species may be influenced by slightly different drivers; [tHg] of walleye was more influenced by water chemistry while that of white sucker was more influenced by the physical structure of the lake and the surrounding watershed. By investigating the drivers of fish mercury accumulation in fish species that occupy different niches, we gain a more comprehensive understanding of whole lake mercury dynamics.

A study investigating temporal trends in walleye Hg concentrations in Wisconsin lakes found that the overall rate of change in walleye Hg between 1982 and 2005 varied with latitude (Rasmussen et al. 2007). Walleye mercury decreased by 0.5% in the northern latitudes and increased by 0.8% in the southern latitudes; the range of latitudes was 4.2°, about half the range investigated in this study. Although latitude was determined to be one of the dominant predictors of fish Hg, Rasmussen et al. (2007) deemed it difficult to separate the effects of individual factors that vary across the latitudinal gradient from latitude itself. Many of the predictor variables that were included in this study varied across the latitudinal gradient within Ontario, potentially independent of climate. These variables include lake pH, DOC and sulfate concentrations, as well as certain drainage basin characteristics. Like the results of Rasmussen et al. (2007), the curvilinear relationships exhibited between various climate variables and fish Hg in this study may be more indicative of overall lake processes that vary across the Ontario landscape than the actual influence of climate.

My use of a field-based, mensurative approach, rather than a controlled, experimental approach necessitates that my results be interpreted with caution. As I have demonstrated, many variables covary across the northern Ontario landscape. Climate exhibits distinct spatial (latitudinal)

patterns, but so do other variables; some of these are likely influenced to some extent by climate (e.g., fish growth rate), whereas others are probably not (e.g., $[SO_4]$, drainage basin slope). Factors that influence fish [tHg] in boreal lakes can be categorized into three groups: those that influence the availability of inorganic mercury, those that influence the conversion of inorganic to organic mercury, and finally those that influence the movement of MeHg up the food chain. Climate may have differential effects on each step in the pathway, and the particular step that limits fish [tHg] can vary in space and time.

Most inorganic mercury in northern Ontario lakes comes from atmospheric dry and wet deposition in the form of elemental mercury (Hg^0), particulate mercury (Hg(p)) and gaseous oxidized mercury (Hg^{2+}). Currently in northern Ontario, mercury deposition declines moving northward, away from North American emission sources (Muir et al. 2009). This depositional gradient also corresponds to decreasing annual precipitation. Patterns of mercury deposition in northern Ontario are likely to be altered in a changing climate. By the year 2050 overall total mercury deposition is predicted to increase in the midwest (including parts of Ontario) as a result of changing precipitation patterns, with greater dry deposition of Hg^0 in summer and greater wet deposition of Hg^{2+} in winter (Megaritis et al. 2014). These predictions are based on present-day anthropogenic emissions. However, the spatial pattern of depositional change could be highly variable depending on combined changes in precipitation and temperature. Precipitation in the north is likely to be more sporadic in the future (Magnuson et al. 1997), and consequently, wet deposition of the more soluble Hg^{2+} may be less frequent. But, higher temperatures may accelerate the atmospheric conversion of Hg^0 to the highly soluble Hg^{2+}, which will then be rapidly removed from the atmosphere through wet deposition.

My results show that in the current climatic conditions, annual precipitation is not a strong predictor of [tHg] in Ontario fish. Although not statistically significant, there is a weak positive relationship between white sucker [tHg] and precipitation. Perhaps this trend is a result of greater Hg^{2+} deposition in regions with higher amounts of precipitation. If this were indeed the case, the reason why this same trend was not seen in walleye [tHg] is not clear.

Atmospheric mercury is deposited directly to lakes and to surrounding watersheds. The main vector for transport of Hg^{2+} and MeHg to lakes from the surrounding catchment areas is DOC (Grigal 2002). The transport of DOC-bound mercury is influenced by drainage basin characteristics, such as mean watershed slope, the ratio of drainage area to lake area, and the percent of the watershed that is composed of wetlands. I found that fish collected from lakes with proportionally greater drainage area to lake area (high D_a:L_a) had higher [tHg]. Similar relationships observed in other studies were attributed to the importance of watersheds as sources of Hg to lakes (Suns and Hitchin 1990, Evans et al. 2005).

My results show that both walleye and white sucker [tHg] were positively influenced by watershed slope, a finding that seems to contradict earlier studies. Mercury concentrations in both lake water and fish have been shown to be higher in topographically flat watersheds (Dennis et al. 2005, Lucotte et al. 2016). Dennis et al. (2005) suggested that the negative relationship between watershed slope and lake MeHg and tHg was due to greater wetland abundance in flatter watersheds and greater rates of transport of DOC-bound Hg to lakes. My data do show that there were a greater proportion of wetlands in low-slope watersheds (results not shown), but I saw that fish had less mercury in lakes with a high proportion of wetlands in the surrounding watershed. Instead of watershed slope influencing the transport of Hg from the watershed to lakes, as suggested by Dennis et al. (2005), perhaps slope affects the production of

MeHg. The overall topography of the watershed extends into the lake, such that lakes in steep watersheds have steeper profiles. These lakes situated in steep watersheds might have a greater proportion of the lake as hypolimnion during summer stratification, when oxygen levels drop. Such anoxic conditions could promote the bacterial production of methylmercury in lake sediments and in the water column. However, I did not find any strong relationships between fish [tHg] and indices of anoxia in this study.

Consistent with earlier studies (e.g. Wren and MacCrimmon 1983, McMurtry et al. 1989, Grieb et al. 1990), my results showed that fish mercury was greater in more acidic lakes with lower conductivity. Although lake pH is in part a function of surficial geology and internal lake processes like photosynthesis (April and Newton 1985), lake pH in parts of Ontario has also been greatly influenced by anthropogenic releases of sulfur dioxide into the atmosphere and the associated deposition of sulfuric acid in the form of acid rain (Jeffries et al. 2003). The addition of sulfur-containing acids to lakes may stimulate mercury methylation by sulfate-reducing bacteria (discussed below). Recent decreases in sulfur released into the atmosphere as a result of emissions regulations (e.g. the 1991 Canada-U.S. Air Quality Agreement; Jeffries et al. 2003) has had the concomitant effects of allowing freshwater food webs to recover (Keller et al. 1992) and reducing mercury in some North American fish populations (Hrabik and Watras 2002, Drevnick et al. 2007).

The conversion of elemental mercury to methylmercury is done in part by sulfate-reducing bacteria found in peatlands, lake sediments and in the water column where oxygen levels are low. Because these bacteria require sulfate as an electron acceptor, conversion rates of elemental to methyl-mercury will be low in low sulfate conditions even if elemental mercury is not limited. The role of sulfate in the methylation of mercury has been highlighted in sulfate-addition

experiments, where methylmercury concentrations increased following increased sulfate loadings to peatlands and lake sediments (Gilmour et al. 1992, Branfireun et al. 1999, Coleman Wasik et al. 2012). My analyses showed that [SO_4] had a positive effect on [tHg] in both species up to roughly 4 mg L^{-1}, but a negative effect at higher concentrations. However, this quadratic relationship ranked highly only in the walleye AICc model ranking exercise. Research by Gilmour et al. (1998) showed that SO_4 may actually inhibit mercury methylation at high concentrations in sediments. A by-product of mercury methylation by sulfate-reducing bacteria is sulfide. Once released into the sediment and lake water, sulfide can bind with inorganic mercury. Due to the charge of some of the resulting sulfide-mercury species (HgS), they cannot passively diffuse through bacterial cells, and thus cannot be methylated (Benoit et al. 2003). Under laboratory conditions, methylation is optimized at 19-48 mg L^{-1} of SO_4 (Benoit et al. 2003); these are much higher concentrations than measured in my study lakes (0.05-8.5 mg L^{-1}). Perhaps in field settings the inhibitory effect of sulfide on mercury methylation is exacerbated by other lake processes. To the best of my knowledge, this curved relationship between fish [tHg] and [SO_4] has not been reported previously in the literature. These results offer support to the aforementioned research indicating that high [SO_4] inhibits mercury methylation, and that the effects of this extend up the aquatic food web.

The role that DOC plays in aquatic Hg dynamics is complicated, and a diversity of relationships have been reported by previous studies. DOC has been shown to have positive (McMurtry et al. 1989, Watras et al. 1998), negative (Grieb et al. 1990), and curvilinear (French et al. 2014) effects on the concentration of mercury in lake water, invertebrates, and fish. My results support the findings of French et al. (2014), where lake [DOC] had a positive effect on mercury accumulation in amphipods up to a threshold concentration of 8.5 mg L^{-1}, above which there was

a negative effect. The threshold [DOC] seen in my study was roughly 12 mg L^{-1} and 9 mg L^{-1} for walleye and white sucker, respectively. The range of [DOC] in the French et al. (2014) study lakes (2.2-23.1 mg L^{-1}) was almost identical to the range included in this study (2.8-24 mg L^{-1}). As discussed above, DOC affects the transport of mercury from the watershed to the lake. DOC also influences the conversion of elemental mercury to methylmercury. This curvilinear relationship is likely the net result of both mechanisms. At low concentrations, French et al. (2014) suggested that DOC promotes mercury bioaccumulation through the transport of DOC-bound elemental Hg and MeHg to lakes. This influx of DOC to the lake may stimulate the microbial activity that releases Hg from the DOC (Golding et al. 2002, French et al. 2014). On the other hand, at high [DOC], Hg^{2+} and MeHg may adsorb more readily to higher molecular weight humic acids, rather than lower molecular weight fulvic acids (French et al. 2014). DOC has been found to inhibit the activity of methylating bacteria possibly as a result of Hg^{2+} forming strong complexes with the DOC, and thereafter being unavailable for microbial uptake (Miskimmin et al. 1992, Barkay et al. 1997). The DOC was not chemically characterised in my study, so it is unknown whether the quality of the DOC influenced the methylmercury production as suggested by French et al. (2014).

I found that white sucker [tHg] was positively related to maximum lake depth, but the reason for this is not clear. Lake depth could influence fish mercury levels indirectly through the effect of water temperature, a variable not included in this study. Deep lakes are generally colder, because solar radiation heats less of the water by volume, and have colder temperatures at depth in particular, due to stratification. Lower water temperatures inhibit mercury methylation and promote demthylation (Ramlal et al. 1993). With this in mind, we might expect to see lower fish mercury in deeper lakes, because there may be less MeHg available to bioaccumulate. Instead, I

found the opposite trend of higher white sucker [tHg] in deeper lakes. Low temperatures also limit fish growth rates (Kitchell et al. 1977) which in turn could result in higher muscle [tHg]. White sucker growth rates were not related to lake depth (results not shown), however, so this is an unlikely explanation.

Lake depth is related to other lake characteristics, such as productivity and anoxia (Nürnberg 1995, 2004). Presumably, deeper lakes with larger anoxic zones could have higher fish mercury concentrations due to the greater area of anoxic water and sediments for methylation (Eckley et al. 2005, Perron et al. 2014). This does not seem to be the case in my study lakes, however. The lake anoxia factors considered in this study, which were a function of lake nutrients, lake depth and surface area, were not related to Hg in either white sucker or walleye. The implications of these findings differ from those of Perron et al. (2014), who found decreased [MeHg] in brown bullhead following the experimental deepening of the oxycline (and the associated decrease in the anoxic zone) in a Quebec lake. However, the decreased brown bullhead [MeHg] was attributed to greater primary and secondary production in the increased oxic zone of the lake and the consequent effects of growth dilution, rather than a decrease in the anoxic zone where mercury is more rapidly methylated (Perron et al. 2014).

The mechanism of how maximum lake depth influenced white sucker Hg was not made clear by my results. Additionally, there is not a clear explanation of why maximum depth was identified as a driver of [tHg] in only white sucker and not walleye. Perhaps since walleye is in a higher trophic position, the apparent influence that lake depth has on either methylmercury production and/or accumulation in white sucker is masked by lake, watershed and biological processes that influence walleye mercury accumulation more strongly.

Looking at the relationships between fish [tHg] and stable carbon and nitrogen isotope signatures in fish muscle provided insight into how MeHg movement through biota is influenced by food web effects. Because I was unable to baseline adjust for all lakes, I compared model outcomes using both baseline-adjusted (subset of lakes) and baseline-unadjusted stable isotope data. The negative relationships between [tHg] and unadjusted fish $\delta^{13}C$ for both species appears to support the results of Power et al. (2002) showing greater mercury accumulation in fish with more negative $\delta^{13}C$ values and presumably relying on more pelagic carbon sources. However, neither baseline-adjusted $\delta^{13}C$ nor $\delta^{15}N$ had an effect on [tHg] for either species. This suggests that the feeding ecology of the fish is not a strong driver of the among-population variation in [tHg]; the significant relationship observed between [tHg] and unadjusted $\delta^{13}C$ may therefore reflect some other process within lakes at the base of the food web that has a common effect on both.

Fish mercury was not strongly related to fish trophic position ($\delta^{15}N$, both baseline-adjusted and unadjusted) across fish populations for either fish species. A positive effect of $\delta^{15}N$ on Hg is evident in food web studies looking at the biomagnification of Hg across multiple trophic levels (Power et al. 2002, McIntyre and Beauchamp 2007, Kidd et al. 2012, Lescord et al. 2015). The fact that I did not find $\delta^{15}N$ to have an effect on fish [tHg] is perhaps not surprising considering I looked at this relationship among populations of the same fish species that presumably have very similar trophic ecologies in all lakes. Differences among lakes in the food chain lengths up to these species were perhaps too slight to register an effect on [tHg] over and above the effects of other factors.

To evaluate growth dilution effects on mercury levels in fish, both growth rate and body condition were considered. Growth rate reflects long-term growth, while body condition reflects recent growth. The negative effect of growth rate on fish [tHg] as a consequence of growth

dilution was the mechanism through which I predicted climate to indirectly influence mercury accumulation in Ontario fish. My prediction was not supported, as mercury concentrations were not related to fish growth rates for either walleye or white sucker.

Although growth rates did not have an effect on mercury levels in either fish species, [tHg] was negatively related to body condition in walleye. This is likely an effect of growth dilution as a result of recent growth. Walleye body condition did vary over the climatic gradient, with fish populations in better condition (i.e. weighed more at 477 mm) in more southern lakes that experience higher annual mean temperatures. This result appears to support my original hypothesis that fish living in warmer climates have lower mercury levels due to growth dilution, resulting from variability in short-term growth rather than lifetime growth. Since body condition ranked highly in the candidate regression models without the presence of temperature or latitude, the negative effect of fish condition on walleye [tHg] may not be strongly driven by the effects of climate, however.

Seasonal changes in fish condition may lead to variable fish mercury concentrations throughout the year. Fish tend to have higher mercury concentrations at the end of the winter when fish activity costs are high, food is scarce, and fish have catabolized some of their own muscle tissue for energy (Cizdziel et al. 2002, Moreno et al. 2015). Such seasonal variation in fish condition may have contributed to variability in muscle [tHg], however were unable to test for this effect.

The mercury data used in this study were acquired over several years, and thus there is likely temporal variability in these data. However, research by Tang et al. (2013) indicated that even over the past 30+ years there has not been major changes in mean total mercury concentrations in large-bodied fish from boreal shield lakes in northern Ontario.

Even though the results of this study did not identify any of the current climatic trends as being dominant drivers of variation in fish mercury concentrations across northern Ontario, this does not mean that fish mercury concentrations will remain unchanged in an actual warming scenario. By using a space-for-time substitution to investigate the potential ways that climate might influence the accumulation of mercury in Ontario fish, I accounted only for the current landscape and lake conditions. Latitudes north of 40° are expected to experience the greatest temperature increases due to climate change (Serreze et al. 2000), and seasonal precipitation patterns in Ontario are predicted to change, with less summer precipitation (Magnuson et al. 1997). Increased temperatures and dryer growing seasons will alter the hydrological processes in the landscape, and result in lessened stream flow and lower water levels. Changes in how surface water moves through the environment will impact the transport of mercury through the watershed. Exaggerated wetting and drying cycles may increase the release of mercury previously stored in anoxic organic sediments (Selvendiran et al. 2008). Additionally, warmer temperatures will alter the range and density of the discontinuous permafrost. The melting of permafrost soils may also result in increased fluxes of mercury to nearby waterbodies (Rydberg et al. 2010). The simple aquatic food webs that currently characterize northern lakes (Hillebrand 2004) will likely be altered in warming conditions. The geographic ranges of warmer fish species will extend north as temperatures rise (Jeppesen et al. 2010), and will subsequently alter the food web structure of northern lakes. With the above in mind, it is clear that although the results of this study are informative, there are still a lot of unknown mechanisms influencing mercury dynamics in Ontario.

Conclusion

Overall, my results do not suggest that climate is currently a primary driver of total mercury accumulation in walleye or white sucker across the northern Ontario landscape. Lake and watershed physical structure and $\delta^{13}C$ best predicted white sucker [tHg], while water chemistry and fish condition best predicted walleye [tHg]. Walleye [tHg] exhibited a curvilinear relationship with lake [SO_4], a relationship not yet demonstrated in nature but suggested in laboratory studies. This novel finding has implications for Hg bioaccumulation in a region that historically was greatly affected by high sulfur dioxide emissions associated with mining and the corresponding deposition of SO_4 to lakes. In recent decades successful emission reductions in North America have resulted in the lessening effects of acid rain in Ontario (e.g. Jeffries et al. 2003). Walleye [tHg] also exhibited a curvilinear relationship with lake [DOC], a relationship seen recently with amphipod [MeHg] in arctic lakes (French et al. 2014). DOC fluxes to lakes are likely to increase due to a warming climate and land-use change. With the additional stresses of a changing climate, it is imperative that we continue to monitor and manage the known drivers of mercury accumulation in our food fish, particularly those factors that are likely to be altered as a result of resource development and other anthropogenic activities.

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Appendices

Appendix A. Length-adjusted population means of [tHg], lifetime growth rate (LGR), $\delta^{15}N$, $\delta^{13}C$, and fish condition (mass at 477 and 440 mm for walleye and white sucker, respectively) for walleye and white sucker populations from 70 Ontario lakes, followed by summary statistics for each of the fish biology variables. Population means are adjusted to 477 and 440 mm TL for walleye and white sucker, respectively. Standard error values are in parentheses.

Lake	Walleye [tHg] (ppm dry)	White sucker [tHg] (ppm dry)	Walleye LGR (mm yr^{-1})	White sucker LGR (mm yr^{-1})	Walleye $\delta^{15}N$ (‰)	White sucker $\delta^{15}N$ (‰)	Walleye $\delta^{13}C$ (‰)	White sucker $\delta^{13}C$ (‰)	Walleye condition (mass at 477 mm)	White sucker condition (mass at 440 mm)
Addie	2.05 (0.37)	0.50 (0.05)	79.01 (4.14)	74.95 (1.86)	10.52 (0.06)	7.88 (0.10)	-28.79 (0.15)	-30.27 (0.21)	1009.42 (17.37)	1025.27 (16.89)
Andy	2.54 (0.51)	0.69 (0.06)	90.22 (3.46)	57.50 (3.60)	13.03 (0.06)	9.85 (0.33)	-27.74 (0.11)	-30.91 (0.45)	993.42 (28.14)	977.72 (18.24)
Anima Nipissing	2.02 (0.46)	0.52 (0.07)	94.25 (3.69)	53.40 (3.85)	8.44 (0.12)	5.52 (0.20)	-25.12 (0.25)	-23.41 (0.88)	968.58 (14.29)	1022.73 (21.38)
Attawapiskat	1.78 (0.17)	0.52 (0.05)	46.37 (2.28)	51.91 (1.33)	11.02 (0.11)	9.3 (0.34)	-29.24 (0.20)	-29.28 (0.43)	1075.33 (22.44)	1058.05 (13.99)
Badesdawa	2.63 (0.27)	0.84 (0.09)	45.29 (1.97)	56.23 (3.01)	11.81 (0.16)	8.74 (0.20)	-27.90 (0.11)	-29.17 (0.26)	971.76 (14.48)	1084.96 (16.46)
Bear	2.44 (0.25)	0.54 (0.02)	84.77 (3.52)	79.95 (3.03)	10.84 (0.06)	8.58 (0.10)	-29.99 (0.10)	-32.28 (0.71)	1003.83 (5.30)	1016.73 (29.19)
Bending	3.77 (0.67)	0.72 (0.17)	68.15 (1.44)	80.38 (3.27)	8.64 (0.17)	6.36 (0.28)	-26.96 (0.30)	-28.17 (0.68)	971.26 (24.01)	1085.06 (35.55)
BigTrout	0.88 (0.22)	0.19 (0.03)	52.88 (0.80)	51.33 (0.64)	11.63 (0.14)	8.32 (0.20)	-24.24 (0.25)	-22.85 (0.27)	1056.23 (18.68)	1077.63 (22.40)
Bigwood	1.24 (0.19)	0.64 (0.09)	107.98 (11.19)	73.82 (4.48)	10.03 (0.10)	7.91 (0.09)	-25.89 (0.19)	-28.41 (0.39)	1039.78 (14.47)	986.48 (20.30)
Bright	1.54 (0.28)	0.58 (0.08)	106.13 (3.20)	63.97 (2.13)	10.71 (0.10)	8.04 (0.05)	-24.88 (0.14)	-23.94 (0.18)	928.36 (21.99)	972.96 (20.73)
Carafel	1.53 (0.23)	0.60 (0.03)	137.43 (8.88)	55.73 (2.41)	10.15 (0.12)	7.39 (0.11)	-27.86 (0.17)	-29.06 (0.68)	1057.81 (23.56)	922.04 (18.80)
Cedar	3.46 (0.53)	1.06 (0.15)	173.76 (9.93)	44.39 (3.76)	10.74 (0.09)	8.00 (0.16)	-28.12 (0.12)	-26.42 (0.63)	1187.41 (53.38)	895.16 (12.30)
Crooked	3.69 (0.36)	0.52 (0.06)	113.33 (4.49)	55.01 (3.13)	11.31 (0.11)	8.91 (0.22)	-28.80 (0.13)	-31.85 (0.55)	1020.21 (38.66)	1015.12 (21.85)
Eabamet	2.62 (0.32)	0.71 (0.08)	46.91 (1.47)	46.76 (2.44)	10.33 (0.08)	8.37 (0.22)	-27.93 (0.15)	-27.20 (0.36)	999.22 (8.73)	913.53 (33.50)
Eagle	5.51 (0.62)	1.28 (0.20)	41.87 (3.05)	50.85 (2.88)	9.82 (0.12)	7.96 (0.13)	-27.74 (0.25)	-27.71 (0.54)	873.98 (20.97)	1161.17 (23.75)
Endikai	4.64 (0.51)	1.07 (0.12)	88.48 (4.71)	59.97 (3.34)	10.09 (0.09)	7.26 (0.19)	-24.76 (0.19)	-26.58 (1.07)	989.81 (8.42)	946.12 (44.60)
Fishtrap	2.14 (0.26)	0.30 (0.01)	45.23 (2.12)	86.20 (5.97)	9.98 (0.09)	5.96 (0.09)	-22.83 (0.09)	-25.22 (0.56)	937.70 (7.67)	965.60 (19.46)
Goldie	2.99 (0.24)	0.76 (0.06)	131.46 (3.34)	61.07 (2.41)	9.66 (0.07)	7.20 (0.20)	-27.23 (0.18)	-26.68 (0.40)	1083.28 (15.5)	888.18 (21.46)
Irwin	4.30 (0.20)	0.74 (0.04)	55.22 (3.42)	46.95 (2.42)	10.28 (0.07)	9.10 (0.13)	-28.63 (0.15)	-29.92 (0.29)	1001.31 (7.95)	1027.08 (20.80)
Isabella	3.17 (0.26)	1.04 (0.28)	129.91 (10.48)	61.81 (3.13)	12.42 (0.11)	9.00 (0.12)	-28.53 (0.18)	-30.27 (0.41)	950.81 (18.26)	1019.92 (25.91)
Jacob	2.34 (0.43)	0.68 (0.11)	79.32 (6.54)	81.32 (3.10)	10.67 (0.12)	8.14 (0.08)	-26.04 (0.14)	-28.91 (0.43)	1076.93 (38.01)	1112.17 (30.84)
Kagianagami	1.88 (0.17)	0.61 (0.07)	69.71 (5.80)	49.93 (4.32)	10.03 (0.07)	6.45 (0.33)	-27.07 (0.36)	-24.44 (0.69)	992.84 (11.11)	1047.92 (54.08)
Kamungishkamo	2.69 (0.31)	0.72 (0.08)	42.93 (2.36)	51.55 (2.69)	9.99 (0.06)	8.16 (0.20)	-29.46 (0.17)	-31.99 (0.54)	958.85 (13.48)	1035.07 (13.87)
Kattawagami	2.78 (0.06)	0.68 (0.15)	51.13 (2.29)	62.81 (1.73)	9.89 (0.09)	6.86 (0.15)	-28.09 (0.15)	-30.49 (0.42)	909.04 (8.16)	980.08 (14.04)
Kenogaming	4.00 (0.54)	0.58 (0.10)	72.96 (2.92)	50.15 (3.09)	10.79 (0.06)	7.77 (0.19)	-30.10 (0.16)	-31.73 (0.58)	939.01 (19.06)	977.42 (18.93)
Kinloch	2.34 (0.11)	0.89 (0.09)	32.60 (2.99)	44.64 (2.54)	11.42 (0.14)	8.09 (0.24)	-27.83 (0.10)	-28.44 (0.22)	926.38 (9.51)	1066.63 (28.36)

Appendix A continued. Length-adjusted population means of [tHg], lifetime growth rate (LGR), $\delta^{15}N$, $\delta^{13}C$, and fish condition (mass at 477 and 440 mm for walleye and white sucker, respectively) for walleye and white sucker populations from 70 Ontario lakes, followed by summary statistics for each of the fish biology variables. Population means are adjusted to 477 and 440 mm TL for walleye and white sucker, respectively. Standard error values are in parentheses.

Lake	Walleye [tHg] (ppm dry)	White sucker [tHg] (ppm dry)	Walleye LGR (mm yr^{-1})	White sucker LGR (mm yr^{-1})	Walleye $\delta^{15}N$ (‰)	White sucker $\delta^{15}N$ (‰)	Walleye $\delta^{13}C$ (‰)	White sucker $\delta^{13}C$ (‰)	Walleye condition (mass at 477 mm)	White sucker condition (mass at 440 mm)
Lang	4.41 (0.40)	0.52 (0.12)	38.47 (5.01)	58.27 (1.64)	9.85 (0.08)	7.05 (0.12)	-27.84 (0.16)	-25.91 (0.44)	894.10 (17.35)	965.03 (18.60)
Lingman	1.16 (0.06)	0.28 (0.05)	36.71 (2.12)	50.90 (1.01)	10.79 (0.17)	6.45 (0.09)	-23.95 (0.34)	-21.97 (0.22)	982.54 (22.63)	1021.66 (14.32)
Little Panache	1.02 (0.04)	0.68 (0.06)	136.70 (3.33)	30.77 (1.07)	12.11 (0.07)	8.5 (0.08)	-26.19 (0.05)	-26.87 (0.62)	1369.92 (30.87)	1076.25 (17.73)
Little Sturge	7.31 (0.57)	0.99 (0.20)	46.18 (2.85)	67.45 (3.86)	10.74 (0.23)	7.77 (0.15)	-27.65 (0.14)	-27.52 (0.36)	912.31 (27.27)	982.40 (24.88)
Long	2.42 (0.35)	0.91 (0.08)	61.07 (2.80)	51.66 (2.82)	10.50 (0.12)	7.13 (0.39)	-29.66 (0.15)	-26.80 (1.06)	1000.67 (9.99)	998.54 (25.78)
Makami	3.28 (0.13)	1.12 (0.09)	77.71 (6.69)	63.85 (3.56)	10.63 (0.08)	7.71 (0.11)	-27.77 (0.20)	-28.67 (0.61)	1028.19 (8.4)	1013.03 (27.06)
Manitou	0.33 (0.26)	0.23 (0.02)	145.56 (2.92)	74.05 (2.59)	10.83 (0.10)	7.70 (0.10)	-25.37 (0.22)	-24.50 (0.10)	1283.99 (63.53)	1044.96 (40.46)
Margot	2.83 (0.20)	0.69 (0.08)	25.80 (1.79)	54.80 (2.23)	11.81 (0.19)	9.54 (0.12)	-29.17 (0.09)	-29.90 (0.36)	998.57 (7.40)	1028.82 (20.99)
Martison	2.48 (0.23)	0.42 (0.05)	25.96 (10.63)	62.08 (3.22)	10.31 (0.20)	7.61 (0.19)	-28.42 (0.07)	-30.67 (0.47)	988.41 (12.1)	1020.08 (11.86)
McInnes	4.06 (0.23)	0.92 (0.10)	25.85 (6.81)	43.89 (3.32)	9.01 (0.08)	6.43 (0.25)	-26.93 (0.31)	-27.49 (1.38)	936.05 (12.3)	965.27 (29.94)
McKay	2.84 (0.69)	0.68 (0.07)	64.68 (1.28)	53.29 (3.88)	10.47 (0.12)	6.59 (0.16)	-28.65 (0.10)	-28.32 (0.44)	853.25 (21.93)	899.32 (13.22)
Menako	2.57 (0.34)	0.58 (0.08)	26.71 (3.75)	60.24 (1.84)	10.65 (0.17)	7.74 (0.23)	-27.86 (0.10)	-27.70 (0.31)	917.81 (8.81)	968.29 (18.67)
Minisinakwa	5.19 (0.62)	0.72 (0.13)	55.11 (1.69)	63.5 (2.33)	10.74 (0.14)	6.83 (0.26)	-30.24 (0.10)	-35.97 (1.49)	974.69 (13.70)	1087.32 (27.28)
Ministic	1.17 (0.30)	0.49 (0.08)	117.17 (3.51)	77.87 (3.82)	9.59 (0.14)	7.51 (0.22)	-26.30 (0.09)	-28.38 (0.40)	1000.39 (48.21)	1010.39 (68.51)
Missinaibi	4.66 (0.57)	1.13 (0.13)	59.73 (3.73)	79.56 (2.77)	10.55 (0.12)	7.87 (0.12)	-25.91 (0.44)	-25.74 (0.52)	903.28 (18.29)	1125.23 (32.57)
Nagagamisis	1.42 (0.17)	0.63 (0.07)	78.54 (3.63)	47.35 (3.23)	11.37 (0.22)	8.46 (0.45)	-29.11 (0.21)	-31.27 (0.34)	1003.43 (10.97)	990.37 (25.48)
Nepewassi	2.60 (0.26)	0.39 (0.02)	64.81 (2.75)	45.84 (3.47)	11.79 (0.23)	10.12 (0.19)	-28.74 (0.30)	-30.33 (0.34)	1036.07 (17.50)	1085.00 (12.15)
Nettogami	1.80 (0.13)	0.45 (0.04)	26.68 (2.57)	52.69 (2.25)	11.43 (0.07)	8.07 (0.24)	-26.27 (0.09)	-27.13 (0.52)	880.66 (7.38)	960.68 (19.36)
Nipissing	1.67 (0.31)	0.66 (0.18)	77.49 (3.11)	54.58 (2.98)	12.15 (0.08)	9.22 (0.15)	-25.12 (0.09)	-25.05 (0.25)	1032.57 (18.12)	1071.76 (16.61)
O'Sullivan	3.02 (0.37)	0.96 (0.10)	69.90 (2.50)	48.01 (3.16)	10.67 (0.15)	8.94 (0.21)	-29.76 (0.10)	-31.81 (0.68)	926.57 (11.92)	984.22 (29.49)
Onaping	2.68 (0.27)	0.81 (0.09)	69.91 (4.81)	70.81 (7.61)	9.84 (0.14)	7.62 (0.18)	-27.49 (0.46)	-28.65 (0.91)	950.17 (12.64)	1076.8 (32.39)
Opeechee	3.69 (0.46)	0.70 (0.04)	101.08 (5.34)	73.09 (1.79)	10.38 (0.07)	8.17 (0.15)	-29.2 (0.15)	-30.76 (0.47)	958.57 (12.08)	1031.83 (20.30)
Pagwachuan	2.25 (0.30)	0.51 (0.10)	89.90 (2.04)	-	9.81 (0.12)	5.85 (0.14)	-26.74 (0.34)	-26.33 (0.34)	969.92 (14.22)	989.3 (26.99)
Panache	1.36 (0.35)	0.36 (0.03)	114.92 (3.96)	60.09 (5.48)	9.93 (0.12)	7.04 (0.18)	-25.84 (0.28)	-22.75 (0.74)	1031.07 (33.67)	1043.75 (19.78)
Pickle	1.47 (0.13)	0.40 (0.06)	75.28 (3.53)	42.45 (1.89)	12.07 (0.15)	8.22 (0.21)	-27.71 (0.19)	-26.55 (0.56)	1235.69 (26.78)	981.26 (17.93)
Pike	3.87 (0.43)	1.10 (0.06)	83.49 (6.96)	68.40 (2.76)	7.77 (0.12)	5.87 (0.16)	-20.66 (0.11)	-22.87 (0.55)	1023.45 (39.99)	976.57 (28.7)
Pine	1.98 (0.30)	0.56 (0.06)	46.88 (2.72)	55.15 (4.58)	13.18 (0.19)	9.70 (0.33)	-28.50 (0.06)	-28.92 (0.64)	929.47 (28.91)	1017.90 (21.36)
Pishabo	1.93 (0.34)	0.47 (0.08)	118.01 (5.71)	81.97 (4.76)	10.42 (0.06)	6.60 (0.12)	-28.62 (0.11)	-25.79 (0.68)	1103.89 (35.46)	998.11 (30.32)
Pishidgi	1.53 (0.21)	0.77 (0.16)	71.76 (2.68)	55.59 (1.83)	9.45 (0.10)	6.66 (0.36)	-26.95 (0.23)	-25.18 (0.82)	1043.08 (13.56)	986.11 (21.24)
Pogamasing	1.07 (0.20)	0.58 (0.08)	140.51 (7.77)	-	8.88 (0.19)	7.08 (0.20)	-25.55 (0.17)	-23.55 (0.65)	1048.72 (27.96)	986.38 (33.06)
Quantz	2.63 (0.25)	0.50 (0.03)	37.89 (11.20)	66.93 (2.48)	11.20 (0.20)	8.14 (0.12)	-28.97 (0.08)	-29.67 (0.40)	1050.45 (25.50)	1098.68 (30.86)
Raven	2.61 (0.49)	0.74 (0.05)	95.52 (3.38)	72.49 (2.44)	10.90 (0.17)	8.47 (0.21)	-27.35 (0.10)	-24.04 (0.60)	958.94 (12.03)	1018.74 (14.81)

Appendix A continued. Length-adjusted population means of [tHg], lifetime growth rate (LGR), $\delta^{15}N$, $\delta^{13}C$, and fish condition (mass at 477 and 440 mm for walleye and white sucker, respectively) for walleye and white sucker populations from 70 Ontario lakes, followed by summary statistics for each of the fish biology variables. Population means are adjusted to 477 and 440 mm TL for walleye and white sucker, respectively. Standard error values are in parentheses.

Lake	Walleye [tHg] (ppm dry)	White sucker [tHg] (ppm dry)	Walleye LGR (mm yr^{-1})	White sucker LGR (mm yr^{-1})	Walleye $\delta^{15}N$ (‰)	White sucker $\delta^{15}N$ (‰)	Walleye $\delta^{13}C$ (‰)	White sucker $\delta^{13}C$ (‰)	Walleye condition (mass at 477 mm)	White sucker condition (mass at 440 mm)
Rock	5.80 (0.47)	0.84 (0.05)	64.56 (1.89)	46.34 (3.52)	12.60 (0.2)	7.31 (0.53)	-27.54 (0.12)	-32.58 (0.49)	1013.03 (9.37)	974.08 (9.54)
Scotia	3.40 (0.39)	1.05 (0.17)	115.82 (4.66)	61.43 (2.62)	9.56 (0.10)	7.73 (0.28)	-26.24 (0.10)	-24.63 (0.27)	1066.67 (16.81)	972.64 (16.66)
Shamattawa	1.51 (0.36)	0.71 (0.09)	50.14 (1.62)	-	11.82 (0.23)	8.14 (0.20)	-29.81 (0.30)	-29.94 (0.8)	992.98 (46.97)	1018.21 (31.89)
Shoofly	1.13 (0.31)	0.64 (0.07)	97.40 (4.83)	58.19 (4.75)	10.65 (0.11)	8.32 (0.14)	-27.54 (0.24)	-29.03 (0.41)	973.06 (24.55)	1022.86 (25.29)
Spruce	1.89 (0.26)	0.47 (0.08)	49.31 (1.89)	50.37 (1.67)	12.29 (0.06)	8.46 (0.33)	-27.27 (0.11)	-27.46 (0.47)	940.6 (16.84)	1048.80 (20.97)
Stull	3.22 (0.33)	1.06 (0.07)	171.36 (8.74)	65.54 (3.50)	8.90 (0.06)	7.33 (0.14)	-28.04 (0.17)	-29.35 (0.35)	1125.16 (31.44)	881.99 (6.55)
Thieving Bear	4.07 (0.45)	1.12 (0.19)	107.46 (7.68)	49.74 (2.94)	10.30 (0.05)	7.38 (0.14)	-29.81 (0.09)	-30.15 (0.67)	1014.79 (8.72)	997.70 (20.19)
Troutfly	0.92 (0.13)	0.28 (0.01)	60.28 (2.56)	54.37 (2.36)	12.21 (0.14)	8.12 (0.13)	-26.84 (0.18)	-27.01 (0.20)	1005.15 (24.49)	958.89 (35.65)
Wanapitei	2.21 (0.44)	0.68 (0.10)	92.22 (2.78)	58.22 (2.51)	10.62 (0.20)	7.45 (0.15)	-25.11 (0.42)	-20.85 (0.54)	939.14 (15.85)	948.60 (35.72)
Wigwascence	1.40 (0.14)	0.55 (0.07)	36.58 (2.66)	57.23 (1.93)	11.12 (0.14)	7.85 (0.14)	-27.51 (0.15)	-27.67 (0.32)	971.61 (9.72)	1040.73 (30.52)
Windy	1.15 (0.34)	0.51 (0.05)	131.11 (12.35)	63.45 (2.34)	9.35 (0.20)	6.94 (0.16)	-24.36 (0.10)	-23.04 (0.30)	1029.67 (35.84)	892.20 (15.33)
Wright	1.92 (0.16)	0.36 (0.05)	48.78 (3.07)	57.26 (3.23)	10.84 (0.15)	8.10 (0.13)	-25.65 (0.35)	-26.63 (0.58)	940.57 (20.88)	1026.43 (12.60)
Mean	2.69	0.68	77.35	59.14	10.64	7.77	-27.33	-27.77	1001.29	1009.24
SE	0.17	0.03	4.28	1.39	0.13	0.12	0.22	0.35	10.41	6.91
Min	0.33	0.19	25.80	30.77	7.77	5.52	-30.24	-35.97	853.25	881.99
Max	8.09	1.28	173.76	86.20	13.18	10.12	-20.66	-20.85	1369.92	1161.17
n	71	71	71	67	71	71	71	71	71	71

Appendix B. Water chemistry data from 64 of the study lakes followed by summary statistics of each of the chemistry parameters.

Lake	Alkalinity (mg L^{-1} $CaCO_3$)	Calcium (mg/l)	DIC (mg/l)	DOC (mg/l)	Cl (mg/l)	Conductivity (uS/cm)	Mg (mg/l)	NH_3 and NH_4^+ (ug/l)	Total Kjeldahl nitrogen (ug/l)	pH	TP (ug/l)	K (mg/l)	Si (mg/l)	Na (mg/l)	SO_4 (mg/l)
Addie	30.20	10.30	6.90	8.1	2.02	73.6	2.64	16	417	7.34	13.00	0.37	3.16	1.27	2.95
Andy	28.80	10.70	6.28	9.5	8.94	113.0	1.78	28	415	7.42	9.01	0.10	5.18	5.18	0.30
Anima Nipissing	5.74	3.28	1.80	2.9	0.21	30.8	0.94	10	148	6.75	4.37	0.20	0.54	0.71	5.85
Attawapiskat	41.80	12.80	8.84	14.0	0.19	87.6	2.78	26	381	7.65	8.23	0.41	1.24	0.56	0.55
Badesdawa	36.20	11.10	9.02	20.8	0.15	79.8	2.62	30	454	7.64	11.50	0.34	1.20	0.48	0.30
Bear	22.20	8.20	6.50	7.4	9.14	87.4	1.91	14	357	6.85	11.25	0.36	0.54	6.03	3.75
Bending	5.65	2.38	1.60	8.0	0.65	21.2	0.57	6	320	6.79	8.83	0.46	1.82	1.07	1.85
Big Trout	49.30	16.20	13.10	6.4	0.52	114.0	3.03	10	236	8.03	6.25	0.36	1.40	0.50	0.45
Bigwood	2.34	2.34	0.82	5.9	0.14	24.4	0.73	8	271	6.54	5.30	0.38	1.58	0.75	5.35
Bright	18.00	5.98	4.36	4.0	5.17	74.4	1.96	42	294	7.33	9.30	0.64	1.64	3.44	5.85
Carafel	3.15	2.92	0.66	3.2	0.54	30.0	0.81	10	232	6.32	13.20	0.23	0.16	0.78	7.90
Cedar	7.15	2.62	1.64	7.5	0.18	27.3	1.00	10	310	6.86	10.30	0.44	1.80	0.87	3.40
Crooked	6.70	3.12	2.36	6.6	11.20	64.4	1.18	24	306	6.30	6.50	0.44	0.40	7.61	3.55
Eabamet	47.00	14.00	10.30	10.9	0.47	96.4	3.12	22	336	7.78	7.70	0.36	0.88	0.50	0.50
Endikai	8.60	4.12	2.40	3.6	0.32	33.6	0.89	2	154	6.84	7.40	0.21	2.24	0.82	4.90
Fishtrap	27.80	10.30	7.28	17.7	0.44	62.8	1.80	22	585	7.51	20.07	0.15	0.40	0.63	0.05
Goldie	8.28	2.90	1.94	6.6	1.45	33.2	0.64	22	277	6.71	16.60	0.23	1.36	2.43	1.85
Irwin	7.41	2.24	2.20	10.1	0.35	22.7	0.65	30	388	6.73	6.85	0.36	0.96	0.94	1.10
Isabella	5.26	2.48	0.90	6.6	3.63	32.6	0.63	10	333	6.81	9.90	0.45	0.96	2.43	2.70
Jacob	18.80	5.60	4.32	9.6	0.52	47.4	1.68	12	434	7.26	11.05	0.34	6.32	1.06	1.85
Kagianagami	53.93	16.30	12.50	7.1	0.18	108.0	3.59	14	259	7.78	9.45	0.61	1.76	0.56	0.60
Kamungishkamo	14.80	5.68	3.84	14.2	0.09	37.0	1.16	28	383	7.16	10.50	0.31	1.18	0.50	0.45
Kattawagami	7.63	3.34	1.60	15.0	0.12	21.2	0.99	12	332	6.83	12.30	0.20	0.60	0.32	0.70
Kenogaming	35.30	10.40	7.90	9.5	0.24	78.1	2.40	56	372	7.68	13.57	0.48	1.96	0.83	2.10
Kinloch	28.60	8.60	6.88	17.8	0.13	63.4	1.84	40	427	7.55	15.80	0.38	0.92	0.48	0.25
Lang	22.90	8.38	5.80	16.0	0.08	55.0	1.83	24	380	7.48	13.00	0.41	0.96	0.50	0.75
Lingman	31.20	10.80	8.16	8.2	0.37	74.8	2.00	18	292	7.87	9.90	0.34	0.60	0.44	0.30
Little Panache	28.60	12.00	7.88	5.4	13.40	119.0	2.64	14	254	7.96	8.90	0.75	0.42	7.72	7.05
Long	66.60	20.80	14.00	9.2	1.90	145.0	4.32	12	291	7.92	8.05	0.59	1.88	1.53	2.15
Makami	22.10	7.82	0.90	8.7	1.42	60.4	1.79	12	330	7.28	6.80	0.35	1.72	1.46	3.15
Martison	14.40	6.52	3.28	15.8	0.11	36.1	1.15	10	360	7.17	12.25	0.21	0.60	0.35	0.25
McInnes	16.30	5.00	3.74	9.0	0.20	39.6	1.32	8	256	7.09	12.20	0.41	1.32	0.62	1.10
McKay	75.80	25.10	19.60	8.7	0.75	177.0	5.37	12	283	8.09	6.83	0.74	1.60	0.97	1.60
Menako	29.90	9.30	7.80	10.8	0.08	67.8	2.07	26	401	7.58	12.70	0.38	1.32	0.41	0.25
Minisinakwa	24.40	8.00	5.30	8.9	1.49	64.1	1.85	20	310	7.44	7.50	0.36	2.36	1.52	3.00
Ministic	2.27	2.08	0.62	3.4	1.43	24.3	0.49	4	305	6.62	6.20	0.37	1.24	1.14	4.90
Missinaibi	27.40	9.40	6.46	9.7	0.25	67.6	2.11	28	326	7.31	7.77	0.38	1.62	0.74	2.80

Appendix B continued. Water chemistry data from 64 of the study lakes followed by summary statistics of each of the chemistry parameters.

Lake	Alkalinity (mg/l $CaCO_3$)	Calcium (mg/l)	DIC (mg/l)	DOC (mg/l)	Cl (mg/l)	Conductivity (uS/cm)	Mg (mg/l)	NH_3 and NH_4^+ (ug/l)	Total Kjeldahl nitrogen (ug/l)	pH	TP (ug/l)	K (mg/l)	Si (mg/l)	Na (mg/l)	SO_4 (mg/l)
Nagagamisis	108.00	35.50	24.70	7.0	1.13	218.0	6.68	8	356	8.25	10.43	0.85	2.78	1.19	1.90
Nepewassi	9.49	3.60	2.60	6.3	0.86	41.3	1.67	62	435	7.06	15.30	0.72	1.00	1.31	5.10
Nettogami	40.50	12.90	8.60	6.6	0.30	83.6	2.98	16	280	7.61	17.20	0.27	1.08	0.65	0.85
Nipissing	17.80	6.68	4.46	4.3	5.34	72.8	2.20	32	336	7.32	15.73	0.63	0.60	4.29	6.35
O'Sullivan	79.20	23.40	16.20	7.4	0.24	156.0	4.87	8	302	7.94	11.25	0.67	1.84	0.73	1.05
Onaping	4.74	2.92	1.70	6.0	3.12	34.8	0.87	2	229	6.66	9.65	0.27	1.92	2.51	4.45
Opeechee	31.90	10.40	8.70	6.5	11.60	107.0	2.64	46	346	7.44	9.37	0.72	0.88	8.02	4.10
Pagwachuan	95.60	31.90	22.00	6.3	0.95	199.0	5.92	4	336	8.20	8.70	0.70	1.96	1.10	1.85
Panache	9.46	5.20	2.16	4.0	5.09	61.1	1.41	2	235	7.18	5.60	0.59	1.02	3.82	8.40
Pickle	54.50	18.50	14.40	24.0	0.40	119.0	3.31	32	363	7.90	8.80	0.52	1.48	0.74	0.90
Pine	31.20	10.80	7.38	6.4	1.91	81.2	2.61	48	444	7.88	13.20	0.21	0.40	1.46	0.20
Pishabo	21.70	7.94	7.08	3.9	0.27	56.0	1.85	24	253	7.14	9.10	0.23	1.26	0.77	4.50
Pogamasing	6.00	3.00	1.88	3.2	0.01	27.0	0.82	2	172	6.90	5.03	0.25	1.56	0.97	0.05
Quantz	29.60	10.20	5.78	15.4	0.11	61.7	1.90	30	415	7.45	15.17	0.22	1.04	0.46	0.30
Raven	11.80	4.64	2.90	6.7	1.31	48.2	1.55	18	308	7.10	7.87	0.42	1.78	1.92	5.65
Rock	18.40	5.38	3.96	4.9	0.64	49.7	1.66	32	254	7.49	7.27	0.40	2.20	1.23	3.45
Scotia	3.71	2.74	1.50	4.9	0.26	25.0	0.81	2	223	6.41	6.17	0.19	1.60	0.81	4.85
Shamattawa	50.90	17.20	11.90	15.2	2.45	115.0	2.19	18	412	7.44	7.80	0.13	1.46	2.37	0.10
Shoofly	98.40	29.80	31.30	3.6	0.43	195.0	4.69	6	202	8.16	6.70	0.78	0.52	1.16	6.40
Spruce	68.00	25.30	14.00	7.8	1.40	133.0	2.53	16	322	7.93	6.03	0.18	0.60	1.52	0.25
Stull	1.30	2.28	0.80	4.6	0.26	24.4	0.76	10	242	6.76	6.57	0.26	1.68	0.83	6.20
Thieving Bear	16.90	5.88	5.22	5.1	0.24	47.0	1.67	28	223	7.19	5.50	0.22	0.98	0.78	4.65
Troutfly	110.00	34.90	23.50	4.9	0.34	214.0	7.30	10	161	8.22	4.80	1.04	1.96	0.90	1.65
Wanapitei	17.00	7.66	4.70	5.0	0.87	58.0	1.86	2	194	7.30	6.20	0.37	2.20	1.15	7.55
Wigwascence	61.20	20.90	17.40	12.1	0.41	129.0	4.30	10	328	7.56	6.27	0.63	3.36	0.84	0.35
Windy	5.50	3.35	1.00	2.8	8.60	62.0	1.08	34	200	6.69	5.80	0.45	2.00	5.64	8.50
Wright	31.20	9.70	7.88	17.2	0.12	70.4	1.98	20	372	7.59	8.65	0.35	0.96	0.43	0.55
Mean	29.95	10.25	7.24	8.6	1.83	76.3	2.19	19.0	314.9	7.33	9.54	0.41	1.50	1.65	2.76
SE	3.37	1.04	0.82	0.6	0.39	6.2	0.19	1.7	10.5	0.06	0.43	0.02	0.13	0.23	0.31
Min	1.30	2.08	0.62	2.8	0.01	21.2	0.49	2	148	6.30	4.37	0.10	0.16	0.32	0.05
Max	110.00	35.50	31.30	24.0	13.40	218.0	7.30	62	585	8.25	20.07	1.04	6.32	8.02	8.50
n	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64

Appendix C. Watershed and lake physical variables for up to 70 study lakes. Watershed variables, including the drainage area to lake area ratio (D_a:L_a) and the wetland area in the surrounding drainage basin to the lake area ratio (W_a:L_a), were estimated from the OMNRF OFAT III online application.

Lake	Drainage area (km^2)	Mean slope (%)	Lake and wetland area (km^2)	Lake area (km^2)	Wetland area (km^2)	D_a:L_a	Percent wetland area (%)	W_a:L_a	Maximum depth (m)	Secchi depth (m)	Anoxia factor (TP)	Anoxia factor (TN)
Addie	32.29	7.93	4.61	3.86	0.75	8.37	2.34	0.20	3.70	2.10	93.80	269.23
Andy	12.75	6.85	3.26	2.72	0.54	4.69	4.26	0.20	14.60	4.50	77.49	271.41
Anima Nipissing	101.27	8.43	28.66	24.36	4.30	4.16	4.25	0.18	66.00	8.00	40.03	194.60
Attawapiskat	21343.13	3.32	8912.09	2082.56	6829.53	10.25	32.00	3.28	-	1.50	-	-
Badesdawa	9054.75	3.52	3799.63	1018.98	2780.66	8.89	30.71	2.73	14.60	3.10	86.39	273.90
Bear	18.98	5.21	3.87	3.57	0.30	5.31	1.56	0.08	9.10	2.65	87.95	259.59
Bending	1537.67	5.22	463.74	408.08	55.66	3.77	3.62	0.14	45.80	2.50	75.77	251.52
Big Trout	4350.17	1.79	2443.49	1095.84	1347.65	3.97	30.98	1.23	-	-	-	-
Bigwood	58.71	4.91	11.87	7.52	4.35	7.81	7.41	0.58	-	3.40	-	-
Bright	185.87	5.09	55.37	49.61	5.76	3.75	3.10	0.12	-	2.70	-	-
Carafel	94.34	7.01	29.36	25.36	4.00	3.72	4.24	0.16	15.30	5.53	95.99	228.15
Cedar	1528.98	8.70	278.67	173.04	105.63	8.84	6.91	0.61	58.50	2.20	82.77	248.36
Crooked	19.03	3.45	4.23	2.44	1.79	7.80	9.41	0.73	21.00	4.15	60.80	248.73
Eabamet	2223.04	2.97	898.42	308.50	589.92	7.21	26.54	1.91	24.00	3.00	66.53	252.21
Eagle	445.13	5.72	102.93	85.92	17.01	5.18	3.82	0.20	24.40	-	-	-
Endikai	475.09	11.90	75.48	59.35	16.14	8.01	3.40	0.27	48.20	5.80	73.16	205.73
Fishtrap	144.28	1.88	125.27	21.87	103.40	6.60	71.67	4.73	-	0.75	-	-
Goldie	83.38	7.34	17.89	14.27	3.61	5.84	4.33	0.25	22.00	2.75	105.25	238.40
Irwin	243.25	5.24	62.13	39.92	22.21	6.09	9.13	0.56	14.00	-	62.63	265.09
Isabella	392.51	5.00	58.30	43.07	15.22	9.11	3.88	0.35	15.40	2.55	81.64	254.61
Jacob	15.16	6.04	2.99	2.19	0.80	6.94	5.28	0.37	11.00	3.45	86.22	272.82
Kagianagami	559.61	3.07	164.71	104.33	60.38	5.36	10.79	0.58	45.00	-	77.10	233.59
Kamungishkamo	281.71	3.38	149.82	38.24	111.58	7.37	39.61	2.92	12.10	1.70	82.10	261.80
Kattawagami	316.26	1.05	242.30	40.09	202.21	7.89	63.94	5.04	6.00	1.40	89.70	250.98
Kenogaming	208.88	4.57	30.47	17.23	13.25	12.13	6.34	0.77	15.80	2.30	95.27	260.09
Kinloch	1190.67	3.55	462.31	165.54	296.78	7.19	24.93	1.79	6.00	2.30	102.32	269.44
Lang	70.90	3.32	30.02	13.40	16.62	5.29	23.44	1.24	23.00	3.30	93.87	262.53
Lingman	561.09	2.83	295.97	104.37	191.60	5.38	34.15	1.84	5.00	3.00	79.39	242.29
Little Panache	7.63	6.70	2.22	1.52	0.70	5.03	9.18	0.46	26.20	5.65	79.79	239.08
Little Sturge	869.96	4.31	85.94	75.81	10.13	11.48	1.16	0.13	31.70	-	-	-
Long	1635.25	5.78	246.24	209.89	36.35	7.79	2.22	0.17	186.10	3.45	70.93	244.36
Makami	665.32	5.07	113.58	80.37	33.21	8.28	4.99	0.41	14.00	3.70	61.18	251.97
Manitou	274.27	1.52	119.86	111.08	8.79	2.47	3.20	0.08	49.10	-	-	-
Margot	1608.13	3.96	569.57	77.43	492.13	20.77	30.60	6.36	18.40	-	-	-
Martison	63.91	1.77	55.67	7.32	48.35	8.73	75.65	6.61	1.80	-	89.67	257.10
McInnes	419.16	4.34	157.25	81.48	75.77	5.14	18.08	0.93	53.40	-	90.56	233.55

Appendix C continued. Watershed and lake physical variables for up to 70 study lakes. Watershed variables, including the drainage area to lake area ratio (D_a:L_a) and the wetland area in the surrounding drainage basin to the lake area ratio (W_a:L_a), were estimated from the OMNRF OFAT III online application.

Lake	Drainage area (km^2)	Mean slope (%)	Lake and wetland area (km^2)	Lake area (km^2)	Wetland area (km^2)	D_a:L_a	Percent wetland area (%)	W_a:L_a	Maximum depth (m)	Secchi depth (m)	Anoxia factor (TP)	Anoxia factor (TN)
McKay	397.54	3.98	72.63	56.98	15.65	6.98	3.94	0.27	48.80	5.00	61.36	240.67
Menako	452.48	3.05	213.43	39.52	173.92	11.45	38.44	4.40	17.70	3.10	91.31	264.78
Minisinakwa	1479.14	4.74	245.48	145.61	99.87	10.16	6.75	0.69	18.30	2.10	65.32	246.47
Ministic	47.07	8.56	11.35	8.63	2.71	5.45	5.76	0.31	31.10	-	58.76	248.89
Missinaibi	1640.71	6.17	277.30	191.34	85.96	8.57	5.24	0.45	94.00	3.50	68.16	251.47
Nagagamisis	299.70	3.25	46.74	38.70	8.04	7.74	2.68	0.21	8.10	2.45	81.88	256.60
Nepewassi	197.17	4.12	34.63	17.90	16.73	11.02	8.49	0.93	16.70	2.10	-	-
Nettogami	58.88	1.06	46.71	20.40	26.31	2.89	44.68	1.29	7.00	-	106.74	238.83
Nipissing	12005.20	5.36	2970.16	1948.25	1021.91	6.16	8.51	0.52	52.00	2.20	101.98	251.79
O'Sullivan	2348.47	2.45	451.92	260.87	191.05	9.00	8.14	0.73	45.70	2.90	86.04	245.05
Onaping	880.46	5.94	182.08	138.01	44.07	6.38	5.00	0.32	53.40	3.70	78.34	224.83
Opeechee	68.83	6.51	13.24	8.33	4.92	8.26	7.14	0.59	9.80	3.60	77.75	256.06
Pagwachuan	199.10	3.78	37.84	31.99	5.85	6.22	2.94	0.18	54.90	3.50	74.93	254.99
Panache	624.27	6.53	188.53	143.30	45.22	4.36	7.24	0.32	56.40	-	-	-
Pickle	91.65	4.25	36.97	17.73	19.24	5.17	20.99	1.08	19.20	3.00	74.06	258.87
Pike	22.06	5.33	5.91	4.18	1.72	5.27	7.82	0.41	3.00	3.00	-	-
Pine	1030.49	1.68	806.64	212.57	594.06	4.85	57.65	2.79	-	-	-	-
Pishabo	8.51	7.39	1.71	1.51	0.20	5.63	2.30	0.13	19.80	4.30	79.49	237.07
Pishidgi	2125.89	4.34	330.57	258.05	72.52	8.24	3.41	0.28	-	-	-	-
Pogamasing	201.38	9.68	40.97	33.57	7.40	6.00	3.68	0.22	34.00	3.50	46.45	204.81
Quantz	79.32	2.06	59.45	10.38	49.08	7.64	61.87	4.73	10.40	-	100.76	267.96
Raven	279.66	5.80	57.98	51.43	6.55	5.44	2.34	0.13	46.90	2.40	72.97	252.37
Rock	574.39	12.90	69.42	47.12	22.30	12.19	3.88	0.47	21.40	3.00	65.92	234.57
Scotia	132.08	7.87	26.93	17.29	9.64	7.64	7.30	0.56	63.10	6.00	59.66	227.45
Shamattawa	4450.69	1.59	3930.30	514.31	3415.99	8.65	76.75	6.64	7.20	2.00	67.13	267.04
Shoofly	14.08	3.40	3.02	2.71	0.31	5.19	2.17	0.11	48.80	8.55	65.31	222.05
Spruce	882.67	1.65	691.63	187.68	503.96	4.70	57.10	2.69	17.10	2.50	55.17	250.15
Stull	51.94	9.51	7.69	5.02	2.67	10.34	5.13	0.53	34.30	5.00	61.65	232.02
Thieving Bear	64.51	8.77	9.37	7.49	1.88	8.61	2.91	0.25	29.00	3.85	54.47	228.11
Troutfly	99.85	3.88	45.48	26.77	18.71	3.73	18.74	0.70	24.40	7.30	44.18	200.12
Wanapitei	2533.41	6.74	539.55	309.30	230.25	8.19	9.09	0.74	141.00	5.00	-	-
Wigwascence	1909.17	3.09	773.67	125.14	648.53	15.26	33.97	5.18	4.00	1.70	55.94	250.13
Windy	88.66	7.53	22.35	14.80	7.54	5.99	8.51	0.51	65.60	5.10	54.31	216.75
Wright	142.66	3.06	62.44	36.54	25.90	3.90	18.16	0.71	13.00	2.50	72.90	260.31
Mean	1236.78	4.98	463.17	164.78	298.40	7.20	16.80	1.26	32.02	3.46	75.84	246.02
SE	370.13	0.30	153.43	44.63	115.70	0.35	2.39	0.20	3.98	0.22	2.16	2.51
Min	7.63	1.05	1.71	1.51	0.20	2.47	1.16	0.08	1.80	0.75	40.03	194.60
Max	21343.13	12.90	8912.09	2082.56	6829.53	20.77	76.75	6.64	186.10	8.55	106.74	273.90
n	70	70	70	70	70	70	70	70	63	55	55	55

Appendix D. Climate estimates generated using a Natural Resources Canada online application for each of the 70 study lakes. Estimates are based on 30 year climate averages for the years 1981-2010.

Lake	Latitude	Longitude	Mean annual temp. (°C)	Annual minimum temp. (°C)	Annual maximum temp. (°C)	Maximum temp. in the warmest month (°C)	Minimum temp. in the coldest month (°C)	Temp. annual range (°C)	Mean temp. during growing season (°C)	Mean temp. during the warmest quarter (°C)	Mean temp. during the coldest quarter (°C)	Mean temp. during the wettest quarter (°C)	Mean temp. during the driest quarter (°C)	Annual ppt. (mm)	Ppt. in the warmest quarter (mm)	Growing season length (days)	Degree days (above 5°C) for growing season
Addie	48.16639	-90.43111	2.06	-3.79	7.91	23.4	-21.0	44.4	12.91	15.8	-13.0	15.8	-11.1	781	282	166	1241
Andy	49.62917	-94.08611	3.12	-1.78	8.02	24.7	-20.6	45.3	14.02	18.2	-13.6	18.2	-11.0	708	301	185	1588
Anima Nipissing	47.25945	-79.90639	2.96	-2.62	8.54	24.3	-20.7	45.1	13.31	16.9	-12.5	15.8	-11.3	871	261	181	1423
Attawapiskat	52.30000	-87.90000	-0.67	-6.09	4.75	22.4	-26.6	49.0	12.35	15.5	-18.5	15.5	-16.5	625	246	159	1113
Badesdawa	51.72805	-89.78472	0.12	-5.16	5.40	23.0	-25.1	48.1	12.81	16.2	-17.5	16.2	-15.1	662	267	163	1216
Bear	48.13250	-79.63445	2.12	-3.65	7.90	23.9	-22.7	46.6	13.14	16.4	-14.0	15.3	-6.4	850	260	174	1351
Bending	49.32028	-92.13750	2.66	-2.70	8.03	24.6	-21.5	46.1	13.72	17.6	-13.8	17.6	-11.4	697	294	180	1494
BigTrout	53.75000	-90.00000	-1.69	-6.69	3.31	21.7	-27.0	48.7	11.86	14.9	-19.9	14.9	-17.6	600	245	154	1011
Bigwood	46.85000	-81.08334	3.67	-1.73	9.08	24.8	-19.0	43.8	13.58	17.5	-11.4	11.9	-10.1	883	244	186	1521
Bright	46.26667	-83.30000	5.29	-0.01	10.59	25.0	-15.2	40.2	13.44	17.8	-8.1	7.4	-7.3	853	220	202	1629
Carafel	46.72917	-80.48750	4.04	-1.51	9.59	25.2	-18.9	44.1	13.75	17.7	-11.0	12.3	-9.8	889	245	189	1570
Cedar	46.02139	-78.47639	4.29	-1.41	9.98	24.8	-17.8	42.5	13.55	17.3	-10.1	6.3	-3.4	960	263	189	1533
Crooked	46.14556	-80.73972	4.96	-0.35	10.26	25.1	-16.7	41.8	13.67	17.9	-9.1	7.1	-2.9	942	230	198	1629
Eabamet	51.52306	-87.85028	-0.11	-5.72	5.51	23.0	-26.0	49.0	12.68	15.8	-17.7	14.5	-15.6	672	256	160	1165
Eagle	50.67139	-94.87278	2.03	-3.38	7.44	24.4	-22.8	47.1	13.47	17.3	-15.1	17.3	-12.5	630	269	178	1435
Endikai	46.58944	-83.03000	4.65	-0.90	10.20	25.1	-16.9	42.0	13.60	17.6	-9.4	6.7	-3.1	925	237	193	1580
Fishtrap	52.35000	-86.40000	-0.94	-6.56	4.69	22.4	-27.1	49.4	12.13	15.0	-18.6	13.8	-16.8	608	232	156	1051
Goldie	48.04472	-83.89555	1.76	-3.99	7.50	22.4	-21.5	43.8	12.35	15.1	-13.1	10.1	-11.8	926	263	167	1155
Irwin	51.57222	-95.05695	1.10	-4.27	6.46	23.7	-24.0	47.6	13.11	16.7	-16.4	16.7	-13.8	625	256	171	1321
Isabella	45.40556	-79.81167	5.55	0.30	10.79	24.8	-15.3	40.2	13.61	18.0	-8.0	1.1	-2.2	1123	249	205	1687
Jacob	48.35194	-90.32889	2.13	-3.90	8.16	24.0	-21.2	45.2	13.17	16.1	-13.1	16.1	-11.2	765	274	165	1267
Kagianagami	50.93139	-87.86333	0.17	-5.54	5.88	23.2	-25.5	48.7	12.65	15.8	-17.1	14.5	-15.2	719	266	162	1175
Kamungishkamo	51.79833	-92.08167	0.28	-4.87	5.43	23.0	-24.6	47.6	12.71	16.2	-17.3	16.2	-14.7	672	276	166	1222
Kattawagami	49.83194	-80.07944	0.29	-5.57	6.15	22.9	-25.1	48.1	12.34	15.1	-16.4	14.0	-8.7	796	249	161	1117
Kenogaming	48.06139	-81.90389	2.42	-3.40	8.24	24.4	-21.9	46.3	13.32	16.7	-13.4	15.5	-5.9	828	245	175	1380
Kinloch	51.94806	-91.03222	0.04	-5.12	5.19	22.9	-25.0	47.9	12.68	16.1	-17.7	16.1	-15.1	663	272	164	1204
Lang	51.58306	-91.51833	0.48	-4.66	5.62	23.2	-24.3	47.5	12.88	16.4	-17.0	16.4	-14.5	678	276	166	1249
Lingman	53.85305	-92.86528	-1.22	-6.31	3.88	22.5	-26.8	49.3	12.27	15.6	-19.7	15.6	-17.2	586	250	158	1095
Little Panache	46.28194	-81.36222	4.62	-0.57	9.80	24.5	-16.7	41.3	13.46	17.6	-9.4	6.7	-3.2	918	230	195	1573
Little Sturge	49.20917	-88.91055	2.12	-3.57	7.81	23.6	-21.5	45.1	12.87	16.1	-13.3	16.1	-11.6	692	244	171	1270
Long	49.47500	-86.89056	1.21	-4.38	6.80	22.7	-22.9	45.6	12.38	15.4	-14.6	14.4	-13.0	803	268	167	1167
Makami	47.73861	-81.83750	2.72	-3.04	8.48	24.5	-21.2	45.8	13.41	16.9	-12.9	15.7	-11.5	821	241	177	1407

Appendix D continued. Climate estimates generated using a Natural Resources Canada online application for each of the 70 study lakes. Estimates are based on 30 year climate averages for the years 1981-2010.

Lake	Latitude	Longitude	Mean annual temp. (°C)	Annual minimum temp. (°C)	Annual maximum temp. (°C)	Maximum temp. in the warmest month (°C)	Minimum temp. in the coldest month (°C)	Temp. annual range (°C)	Mean temp. during growing season (°C)	Mean temp. during the warmest quarter (°C)	Mean temp. during the coldest quarter (°C)	Mean temp. during the wettest quarter (°C)	Mean temp. during the driest quarter (°C)	Annual ppt. (mm)	Ppt. in the warmest quarter (mm)	Growing season length (days)	Degree days (above 5°C) for growing season
Manitou	45.77750	-81.98361	5.37	1.01	9.73	23.3	-13.5	36.8	12.90	17.3	-7.2	1.6	-2.4	913	207	206	1557
Margot	52.47417	-93.15056	-0.09	-5.29	5.10	23.0	-25.2	48.2	12.66	16.1	-18.0	16.1	-15.4	636	265	163	1192
Martison	50.40417	-83.14555	0.53	-5.32	6.38	23.4	-25.3	48.7	12.62	15.7	-16.4	14.5	-14.8	753	241	164	1181
McInnes	52.21556	-93.72972	0.14	-5.03	5.31	23.0	-24.8	47.8	12.69	16.1	-17.6	16.1	-15.0	643	266	165	1208
McKay	49.61333	-86.43806	1.07	-4.57	6.72	23.1	-23.4	46.5	12.58	15.7	-15.1	14.5	-13.4	792	268	166	1191
Menako	52.07833	-90.19389	-0.23	-5.42	4.95	22.7	-25.4	48.1	12.62	15.9	-18.0	15.9	-15.5	656	267	161	1166
Minisinakwa	47.66333	-81.73833	2.85	-2.89	8.59	24.6	-21.0	45.6	13.42	17.0	-12.8	15.8	-11.4	818	240	179	1423
Ministic	46.56083	-81.56889	3.98	-1.48	9.44	24.7	-18.1	42.7	13.51	17.3	-10.5	12.0	-9.4	913	241	187	1518
Missinaibi	48.35667	-83.69139	1.80	-4.14	7.73	23.1	-22.3	45.4	12.69	15.6	-13.6	10.4	-12.2	852	249	168	1222
Nagagamisis	49.47722	-84.65722	0.97	-5.02	6.96	23.6	-24.0	47.5	12.68	15.6	-15.4	14.4	-13.7	704	228	163	1188
Nepewassi	46.36666	-80.63333	4.62	-0.92	10.16	25.4	-17.8	43.2	13.81	18.0	-9.9	6.7	-3.4	922	237	194	1617
Nettogami	50.20028	-80.54444	0.13	-5.57	5.84	22.7	-25.3	48.0	12.20	15.1	-16.6	14.0	-9.0	786	247	162	1103
Nipissing	46.28333	-80.00000	4.65	-1.09	10.39	25.6	-17.9	43.5	13.79	17.9	-9.8	6.8	-3.3	955	250	194	1615
O'Sullivan	50.42167	-87.05666	0.54	-5.19	6.28	23.4	-24.9	48.3	12.71	15.9	-16.4	14.6	-14.6	740	266	164	1199
Onaping	47.06667	-81.50000	3.22	-2.31	8.74	24.5	-19.7	44.2	13.38	17.1	-11.9	11.5	-10.6	872	245	182	1441
Opeechee	46.78250	-79.82806	3.74	-1.85	9.33	24.8	-19.2	43.9	13.47	17.3	-11.2	12.1	-10.0	938	264	187	1513
Pagwachuan	49.71750	-86.08861	1.08	-4.64	6.80	23.5	-23.6	47.1	12.73	15.9	-15.3	14.7	-13.6	770	261	166	1212
Panache	46.25000	-81.33334	4.79	-0.35	9.92	24.6	-16.4	41.0	13.54	17.7	-9.2	6.9	-3.1	912	226	196	1594
Pickle	51.45417	-90.23778	0.54	-4.66	5.75	23.2	-24.4	47.6	12.99	16.5	-16.9	16.5	-14.5	666	270	166	1265
Pike	47.49028	-79.86361	2.85	-2.78	8.47	24.4	-21.2	45.6	13.33	16.9	-12.8	15.8	-11.6	823	253	181	1423
Pine	54.15000	-85.03333	-2.97	-8.27	2.32	20.3	-28.5	48.8	10.57	12.8	-20.6	12.0	-20.6	520	199	145	763
Pishabo	47.11833	-79.71833	3.04	-2.54	8.63	24.3	-20.4	44.7	13.29	16.9	-12.2	15.8	-11.1	916	269	181	1422
Pishidgi	50.03333	-89.08334	1.27	-4.53	7.08	23.7	-23.8	47.6	13.00	16.3	-15.3	15.1	-13.4	732	261	167	1268
Pogamasing	46.96778	-81.83583	3.31	-2.23	8.85	24.4	-19.4	43.8	13.35	17.0	-11.6	11.5	-10.4	889	245	182	1434
Quantz	51.16528	-85.38389	0.01	-5.87	5.89	23.3	-26.1	49.4	12.54	15.6	-17.3	14.4	-15.5	665	239	161	1151
Raven	48.05305	-79.55194	2.29	-3.54	8.13	24.1	-22.5	46.6	13.19	16.6	-13.7	15.4	-12.4	844	259	176	1370
Rock	46.43472	-83.77250	5.01	-0.50	10.52	25.0	-15.9	40.9	13.34	17.5	-8.5	7.2	-7.6	904	231	199	1587
Scotia	47.06861	-81.37833	3.22	-2.29	8.72	24.5	-19.8	44.3	13.40	17.1	-12.0	11.5	-10.7	872	246	182	1443
Shamattawa	54.16500	-85.68916	-2.80	-8.06	2.46	20.6	-28.3	48.9	10.81	13.1	-20.5	12.3	-20.5	517	200	146	801
Shoofly	47.22639	-81.37945	3.12	-2.44	8.69	24.6	-20.1	44.7	13.44	17.1	-12.2	11.5	-10.9	850	243	181	1442
Spruce	54.33445	-85.01361	-3.19	-8.41	2.03	20.1	-28.6	48.7	10.49	12.5	-20.8	11.9	-20.8	515	197	142	736
Stull	47.26194	-80.82278	2.88	-2.61	8.37	24.3	-20.5	44.8	13.30	16.9	-12.6	11.3	-11.3	864	251	180	1414

Appendix D continued. Climate estimates generated using a Natural Resources Canada online application for each of the 70 study lakes. Estimates are based on 30 year climate averages for the years 1981-2010.

Lake	Latitude	Longitude	Mean annual temp. (°C)	Annual minimum temp. (°C)	Annual maximum temp. (°C)	Maximum temp. in the warmest month (°C)	Minimum temp. in the coldest month (°C)	Temp. annual range (°C)	Mean temp. during growing season (°C)	Mean temp. during the warmest quarter (°C)	Mean temp. during the coldest quarter (°C)	Mean temp. during the wettest quarter (°C)	Mean temp. during the driest quarter (°C)	Annual ppt. (mm)	Ppt. in the warmest quarter (mm)	Growing season length (days)	Degree days (above 5°C) for growing season
Thieving Bear	47.17944	-79.82611	3.08	-2.52	8.67	24.4	-20.5	44.9	13.28	17.0	-12.3	15.9	-11.1	888	263	183	1431
Troutfly	51.69750	-88.89306	-0.26	-5.67	5.15	22.7	-25.8	48.5	12.52	15.8	-17.9	14.3	-15.7	676	265	161	1152
Wanapitei	46.75000	-80.75000	4.21	-1.23	9.66	25.3	-18.6	43.9	13.90	18.0	-10.8	12.5	-9.6	865	239	190	1600
Wigwascence	52.45417	-89.41000	-0.63	-5.87	4.61	22.4	-26.1	48.6	12.42	15.6	-18.5	15.6	-16.2	636	257	159	1129
Windy	46.59917	-81.43889	4.05	-1.40	9.51	24.9	-18.1	43.0	13.61	17.5	-10.6	12.1	-9.4	904	239	188	1545
Wright	51.32750	-90.96056	0.69	-4.49	5.87	23.3	-24.1	47.4	13.01	16.6	-16.7	16.6	-14.2	684	276	167	1272
Mean	49.20228	-85.18404	1.87	-3.61	7.36	23.7	-22.1	45.7	12.96	16.4	-14.2	13.1	-11.6	779.66	251.16	174.10	1323.24
SE	0.29930	0.56774	0.25	0.26	0.26	0.1	0.4	0.3	0.08	0.1	0.4	0.4	0.5	15.28	2.41	1.75	25.33
Min	45.40556	-95.05695	-3.19	-8.41	2.03	20.1	-28.6	36.8	10.49	12.5	-20.8	1.1	-20.8	515	197	142	736
Max	54.33445	-78.47639	5.55	1.01	10.79	25.6	-13.5	49.4	14.02	18.2	-7.2	18.2	-2.2	1123	301	206	1687
n	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70